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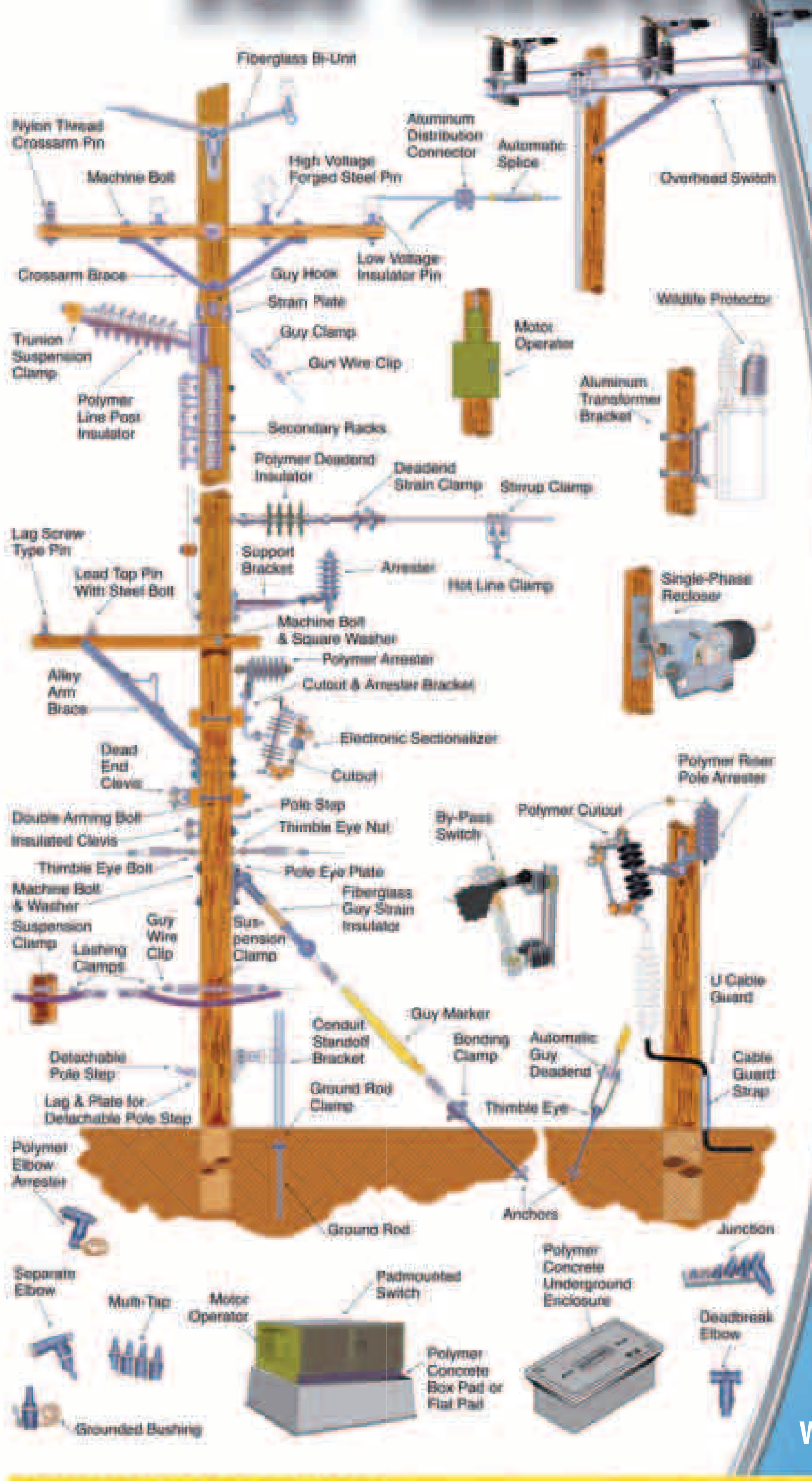

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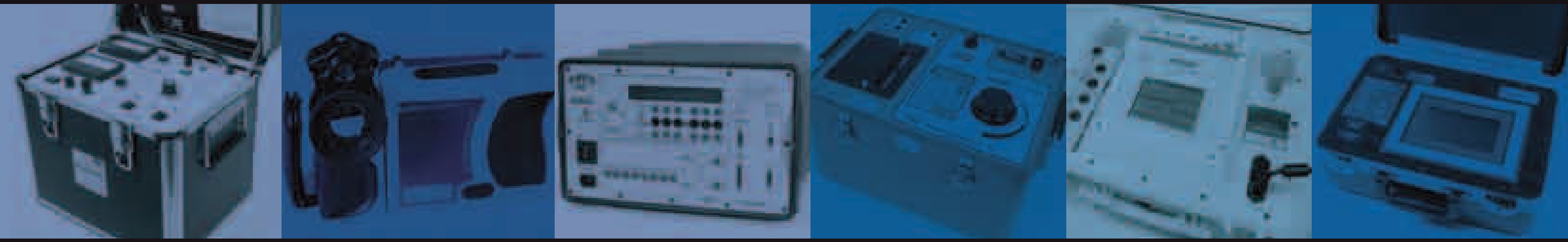

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UNDRSTANDING PRODUCT CERTIFICATION MARKS AND THE PRODUCT TESTING AND CERTIFICATION PROCESS

Randall W. Luecke, President, CSA International

Every day, retail buyers, merchandising managers, quality assurance managers and others in retail operations make important decisions about which products will appear on their stores' shelves. While factors such as style or fashion trends, new technology, brand popularity, promotional support, and others can play important roles in the selection process, the presence of a certification mark from a qualified laboratory can be a key prerequisite of product acceptance.

Product certification marks — such as the CSA mark, the CSA Blue Star, or the UL mark — are found on a wide range of products, including electrical and gas appliances, consumer electronics, plumbing products, water purification units, heating and ventilating equipment and lighting products. Although many retailers today require that certification marks appear on the products they sell, confusion remains about what certification marks mean, who is qualified to perform product testing and certification and issue the marks, and how testing and certification organizations can assist retailers in protecting their customers, and their businesses, from products that don't meet accepted standards for safety and/or performance.

If retail buyers and quality assurance managers do not have a clear understanding of the marks and the companies who issue them, it can prevent them from better assuring that the products in their stores meet applicable standards for safety and/or performance. And it may unnecessarily limit the products they make available to their customers, placing their stores at a competitive disadvantage.

INDEPENDENT THIRD-PARTY TESTING PROTECTS RETAILER AND CONSUMER INTERESTS

Product certification marks are the result of an independent, third-party testing and certification process. As such, they provide credible evidence that products bearing them comply with applicable standards for safety and/or performance.

Product certification marks must appear on products and may be included on product packaging. They differ from other product and packaging markings such as brand name or logo identification, marketing endorsements, promotional approval seals and similar markings that are directly controlled by the product manufacturer.

Product certification marks provide clear evidence that a product has undergone independent, third-party testing and certification performed by an accredited testing and certification organization (referred to in this article as a laboratory). Display of certification marks is not at the discretion of the product manufacturer. These marks may only be used on qualified products under license from the laboratory that tested the product and confirmed that it conforms to applicable national, international or other standards for safety and/or performance.

To qualify for certification marks, manufacturers submit samples of their products to a testing laboratory. The laboratory evaluates these products under controlled conditions to determine if they meet applicable standards. Only product designs that successfully pass all required tests are entitled to bear the laboratory's certification mark. These marks are a visible and credible indicator to retail buyers, quality managers and consumers that the products meet the requirements of the applicable standards.

To ensure that the product continues to comply with the applicable standards over time, the laboratory conducts a series of unannounced, on-site inspections as mandated by the Occupational Safety and Health Administration (OSHA) for products sold in the U.S., and Standards Council of Canada (SCC) for products sold in Canada.

If the laboratory finds that a product does not meet the requirements of the standards during these follow-up inspections, corrective action is required which may include reworking, recalling and/or delisting the product.

PRODUCT TESTING AND CERTIFICATION — THE STAKEHOLDERS

Three stakeholder groups participate in the product testing and certification process (Figure 1): product manufacturers, standards developers and the laboratories.

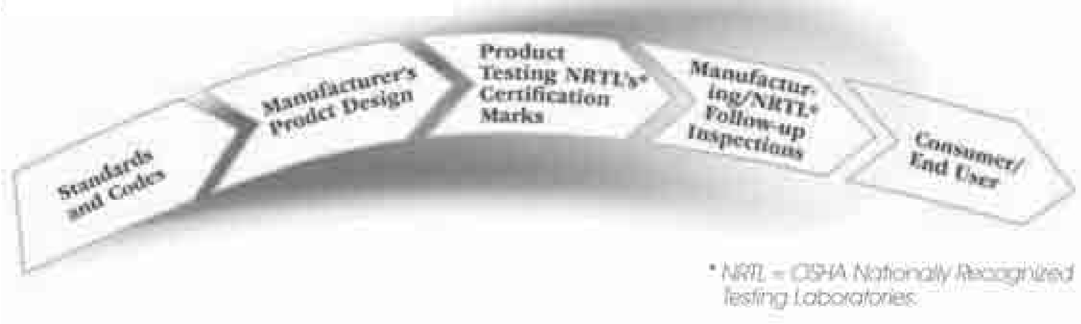
Product manufacturers are the companies that make the drills, refrigerators, grills, decorative lighting, heating and cooling systems, electrical and electronic equipment, as well as plumbing and other products sold by retailers, distributors and manufacturers.

They must be aware of the applicable U.S., Canadian, and international standards when designing their products, and selecting the components and materials used in their products when manufacturing the products.

Standards developers are the organizations responsible for creating the standards or facilitating standards development. Often, they are supported by technical committees that include representatives from government, industry, retailers, consumer groups, regulators and end-users affected by the standards. These organizations develop the standards for a particular product and work in cooperation with standards publishers. In the U.S., standards developers commonly delegate the responsibility for publishing, maintaining, and distributing standards to organizations such as the American National Standards Institute (ANSI) the American Society for Testing and Materials (ASTM), CSA America, the National Sanitation Foundation

(NSF) and Underwriters Laboratories (UL). In addition, standards developers are working together to produce harmonized standards. For example, tri-national (Canada, U.S. and Mexico) standards are developed through CANENA, the Spanish acronym for the Council for Harmonization of Electrotechnical Standards of the Nations of the Americas. Through standards harmonization, CANENA aims to increase opportunities for trade among the three countries. The standards are published jointly by the Canadian Standards Association in Canada, Underwriters Laboratories Inc. (UL) in the U.S. and Mexico's Asociación de Normalisación y Certificación del Sector Eléctrico (ANCE).

Figure 1. Product Certification Process


Standards and Codes
Manufacturer's Prodct Design
Product Testing NRTL's* Certification Marks
Manufacturing/NRTL* Follow-up Inspections
Consumer/ End User
* NRTL = OSHA Nationally Recognized Testing Laboratories

The laboratories are independent organizations accredited/recognized by various governmental or national organizations to provide testing to national standards (e.g. OSHA, ANSI and Standards Council of Canada in Canada). These laboratories are hired by manufacturers to test their products and certify that the products meet the applicable standards. When a product is certified, the manufacturer is licensed to use the appropriate approval mark issued by the laboratory. The laboratory also makes available to the public a list of the products it has certified. The services offered by the laboratories include testing and certification of the original product design ("prototype") and regular follow-up inspections conducted at the factory where the mark is applied to the product to ensure that the products continue to conform to the standards.

In addition to operating offices and laboratories in the U.S. and Canada, to serve manufacturers with North American design and production operations, organizations such as CSA International have opened offices and established partnerships outside of North America to support the needs of manufacturers with global design and manufacturing centers or outsourcing arrangements. These same global partnerships often support retailers who require local inspection services to support direct sourcing of house or captive brands from offshore regions.

UNDERSTANDING THE DISTINCT ROLES OF STANDARDS DEVELOPERS AND THE LABORATORIES

It is important to understand the difference between the laboratories and standards developers. In some instances, separate divisions of the same organization are involved in testing products/issuing certification and in publishing the standards that the products are tested against.

When an organization is involved in both standards publishing and product certification, these activities are performed independently and separately to avoid conflicts of interest.

Within CSA Group, for example, CSA America is responsible for publishing U.S. standards, the Canadian Standards Association publishes standards for Canada, and CSA International is a North American product testing and certification organization.

Sometimes the name (or a portion of the name) of an organization well known for its testing and certification activities appears in the name of standards published by that organization's standards division (for example, UL standard 507 for electric fans, or CSA standard Z21.47/2.3 for gas-fired central furnaces). This does not mean that a product must be tested and certified by the company whose name appears on the standard. So-called "CSA standards", "NSF standards", "UL standards", and others, are available to all qualified and accredited testing laboratories for use in testing and certifying products.

RECOGNITION AND ACCREDITATION MEANS CHOICES

A laboratory must be recognized or accredited to test a particular product and issue certification. Recognition/Accreditation means that the laboratory has proven that it possesses the necessary competence, capabilities, calibration and control programs, independence, and reporting and complaint handling procedures. In the U.S., OSHA recognizes laboratories as qualified to test electrical and gas products and to certify those that meet U.S. standards. OSHA-recognized facilities are known as Nationally Recognized Testing Laboratories (NRTLs).

To receive U.S. recognition, a laboratory must submit application materials to OSHA.

OSHA then performs an application review and an assessment review of the laboratory's organization, programs and test facilities. The preliminary findings are published in the Federal Register to allow public comment. Following a waiting period, OSHA publishes a second notification and responds to any comments. If the application is successful, this second notice signifies that the laboratory has been approved as an NRTL. CSA International and Underwriters Laboratories are two examples of OSHA NRTLs. Both of these organizations are considered equally qualified to perform testing of products covered by their OSHA recognitions.

All NRTLs test products against the same sets of standards, regardless of who wrote or published them. For example, since CSA International and UL are both NRTLs for electrical products, a floor lamp certified by one laboratory has successfully met the same criteria as a floor lamp certified by the other.

All NRTLs also conduct unannounced follow-up inspections to ensure that the products they certify remain in compliance with applicable standards. The frequency of these inspections is set by OSHA guidelines; some NRTLs conduct more frequent inspections based on production volume, product liability risk or manufacturer compliance history.

In addition to OSHA, other accreditation bodies accredit laboratories as qualified to test electrical, gas and other classes of products for the U.S. market. These include ANSI, the International Accreditation Services (IAS)/International Code Council (ICC), the National Voluntary Laboratory Accreditation Program (NVLAP) and the American Society of Safety

Engineers (ASSE).

THE PRODUCT TESTING AND CERTIFICATION PROCESS

To begin the product testing and certification process, a product manufacturer requests a project estimate from one or more laboratories. Once the manufacturer receives the estimate(s), they choose a laboratory based on factors such as price and delivery time.

The manufacturer then makes available to the laboratory product samples and data, such as a materials list, schematic diagrams, and information about the components used in the product.

Upon successful completion of evaluation and testing, the manufacturer will receive confirmation from the laboratory, typically in the form of a descriptive and test report, which specifies that the product does comply with the applicable requirements. The product will then be publicly listed by the laboratory. The manufacturer can then label the product with the certification mark of the laboratory. The National Electrical Code provides the following description of what it means for a product to be listed and labeled:

Listed. Equipment, materials, or services included in a list published by an organization that is acceptable to the authority having jurisdiction and concerned with evaluation of product or services, that maintains periodic inspection of production of listed equipment or materials or periodic evaluation of services, and whose listing states that the equipment, material or services, either meets appropriate designated standards or has been tested and found suitable for a specified purpose.

Labeled. Equipment or materials to which has been attached a label, symbol or other identifying mark of an organization that is acceptable to the authority having jurisdiction and concerned with product evaluation, that maintains periodic inspection of labeled equipment or materials and by whose labeling the manufacturer indicates compliance with appropriate standards or performance in a specified manner.

Most laboratories, including CSA International, post directory listings on their websites, where any interested party can verify whether or not a particular product has been certified.

WHAT THE MARKS MEAN

Product certification marks are a visible indicator that a product or component meets applicable standards for safety and/or performance. Some of the marks issued by accredited/recognized laboratories and commonly found on products certified to applicable U.S. national standards are CSA, UL, NSF, ETL and TUV. Here are some example marks from CSA International and explanations of when they are used.

The CSA mark indicates that a product meets applicable Canadian standards including those from CSA.

The CSA US mark indicates that a product meets applicable U.S. standards, including those from ANSI, ASME, ASSE, ASTM, NSF, CSA America and UL.

The CSA C/US mark signifies that the product meets applicable U.S. and Canadian standards, including those from CSA, CSA America, ANSI, ASME, ASSE, ASTM, NSF and UL.

The CSA Blue Star, found on gas-fired products, demonstrates that they meet U.S. standards for gas-fired products published by ANSI and CSA America.

The CSA Blue Flame, found on gas-fired products, demonstrates that they meet Canadian standards for gas-fired products published by CSA.

THE BENEFITS OF COMPETITION

Because multiple laboratories have attained accreditation/recognition to test and certify various types of products, product manufacturers have the freedom and flexibility to select an accredited/recognized laboratory for a particular certification project based on factors such as delivery time, price and convenience.

Since different laboratories test and evaluate similar products against the same standards, retail buyers can select products for their stores based on brand, price and quality, rather than who did the testing and evaluation.

A competitive, open testing and certification marketplace helps manufacturers bring their products to market as quickly and economically as possible, while also ensuring that they are subjected to the testing called for by the applicable standards. This can help assure qualified products, competitively priced, will be available to retailers without shortages or backorder delays.

Retailers can take advantage of this qualified competition, and ensure access to the broadest possible selection of products, by ensuring that their product selection practices are not unduly restrictive. For example, a policy or practice that accepts products tested and certified by an accredited/recognized laboratory protects retailers and consumers against nonconforming products without placing unnecessary limits on product selection.

In contrast, a purchasing policy requiring products certified by a particular laboratory unnecessarily limits the range of options available to retail buyers.

By becoming more familiar with the product testing and certification process, and taking advantage of the benefits offered by a competitive system of testing and certification, retailers can ensure that their customers have continued access to new and innovative products that meet their expectations for performance and safety. The competitive system also provides manufacturers options for cost, service and delivery.

UNDERSTANDING INSULATION RESISTANCE TESTING

AEMC Instruments

WHY HAVE AN INSULATION TESTING PROGRAM?

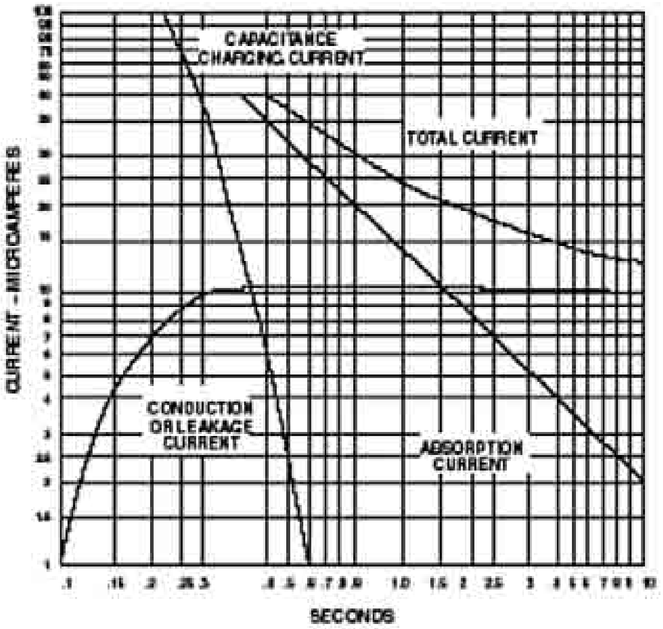
A regular program of testing insulation resistance is strongly recommended to prevent electrical shocks, assure safety of personnel and to reduce or eliminate down time. It helps to detect deterioration of insulation in order to schedule repair work such as: vacuum cleaning, steam cleaning, drying and rewinding. It is also helpful when evaluating the quality of the repairs before the equipment is put back into operation.

WHAT CAUSES INSULATION FAILURE?

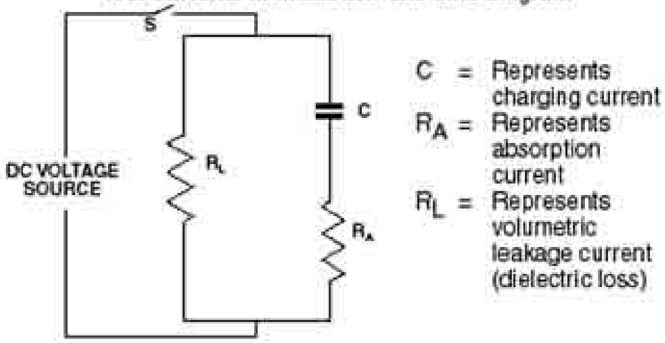
Some of the more common causes of insulation failure include: excessive heat or cold, moisture, dirt, corrosive vapors, oil, vibration, aging and nicked wiring. What tests are used to detect insulation deterioration? There are numerous maintenance tests for assessing insulation quality. The three tests discussed here are used primarily to test motor, generator and transformer insulation.

WHAT EQUIPMENT IS NECESSARY FOR CONDUCTING INSULATION RESISTANCE TESTS?

- Megohmmeter with a timed test function
- Temperature indicator
- Humidity meter (not necessary if equipment temperature is above the dew point)



Test Currents in Insulation One Line Diagram


S
C
R_L
R_A
DC VOLTAGE SOURCE
C = Represents charging current
R_A = Represents absorption current
R_L = Represents volumetric leakage current (dielectric loss)

TEST CURRENTS IN INSULATION

Total current in the body of the insulation is the sum of three components

- Capacitance Charging Current
- Absorption Current
- Leakage or Conduction Current

INSULATION RESISTANCE READINGS

Readings are time dependent

- at the start, capacitance is what you see first
- at or about one minute, absorption
- at 10 minutes, reading is mainly leakage current

These changing readings are best seen with analog bargraphs on digital instruments or needle movement on analog instruments.

SPOT READING TEST

METHOD

For this test, the megohmmeter is connected across the insulation of the windings of the machine being tested. A test voltage is applied for a fixed period of time, usually 60 seconds and a reading is taken. The spot reading test should only be carried out when the winding temperature is above the dew point. The operator should make a note of the winding temperature, so that it will be possible to correct the reading to a base temperature of 20°C.

TEST DURATION

To obtain comparable results, tests must be of the same duration. Usually the reading is taken after 60 seconds.

INTERPRETATION OF RESULTS

Proper interpretation of spot reading tests requires access to records of results from previous spot reading tests. For conclusive results, only use results from tests performed at the same test voltage for the same amount of time, and under similar temperature and humidity conditions. These readings are used to plot a curve of the history of insulation resistance. A curve showing a downward trend usually indicates a loss of insulation resistance due to unfavorable conditions such as: humidity, dust accumulation, etc. A very sharp drop indicates an insulation failure. See Figure 1.

Example of the variation of insulation resistance over a period of years:

At A, the effect of aging and dust accumulation is shown by decreasing values.

At B, the sharp drop indicates an insulation failure.

At C, the insulation resistance value after the motor has been rewound.

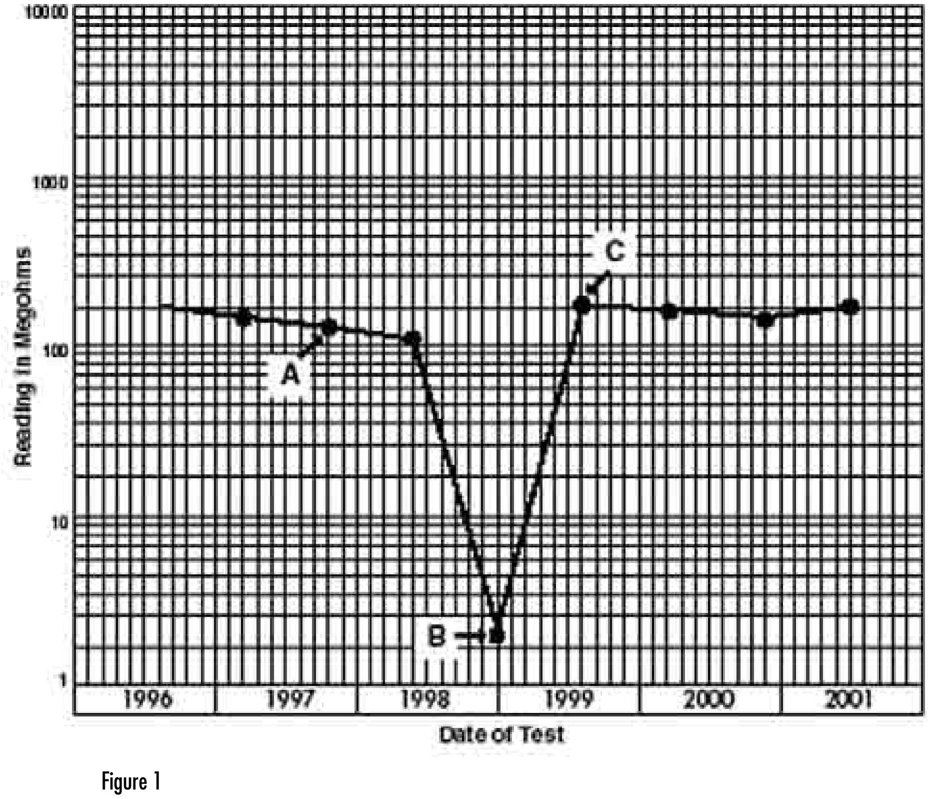


Figure 1

(1) Dew point temperature is the temperature at which the moisture vapor in the air condenses as a liquid.

TIME-RESISTANCE TESTING METHOD

This method is fairly independent of temperature and often can give you conclusive information without records of past tests. It is based on the absorption effect of good insulation compared to that of moist or contaminated insulation. Simply take successive readings at specific times and note the differences in readings (see curves, Figure 2). Tests by this method are sometimes referred to as absorption tests.

Good insulation shows a continual increase in resistance (see curve D) over a period of time (in the order of 5 to 10 minutes). This is caused by the absorption; good insulation shows this charge effect over a time period much longer that the time required to charge the capacitance of the insulation.

If the insulation contains moisture or contaminants, the absorption effect is masked by a high leakage current which stays at a fairly constant value ? keeping the resistance reading low (R = E/I) (see curve E).

The time-resistance testing is of value because it is independent of equipment size. The increase in resistance for clean and dry insulation occurs in the same manner whether a motor is large or small.You can compare several motors and establish standards for new ones, regardless of their horsepower ratings.

Figure 2 shows how a 60-second test would appear for good and bad insulation. When the insulation is in good shape, the 60-second reading is higher that the 30-second reading.

A further advantage of this two reading test is that it gives you a clearer picture, even when a “spot reading” says the insulation looks ok.

Time-resistance tests on large rotating electrical machinery - especially with high operating voltage - require high insulation resistance ranges and a very constant test voltage. A heavy-duty megohmmeter serves this need. Similarly, such an instrument is better adapted for cables, bushings, transformers, and switchgear in the heavier-duty sizes.

Test Methods - Time-Resistant Tests Dielectric Absorption Ratio (DAR)

- The ratio of 60 seconds/30 seconds
- less than 1 = failed
- 1.0 to 1.25 = OK
- 1.4 to 1.6 = excellent
- Note: This is not a commonly used test

STEP VOLTAGE TEST

METHOD

In this test, the operator applies two or more test voltages in steps. The recommended ratio for the test voltage steps is 1 to 5. At each step, test voltage should be applied for the same length of time, usually 60 seconds. The application of increased voltage creates electrical stresses on internal insulation cracks. This can reveal aging and physical damage even in relatively dry and clean insulation which would not have been apparent at lower voltages.

TEST DURATION

A series of "steps," each step lasting 60 seconds.

INTERPRETATION OF RESULTS

Compare the readings taken at different voltage levels, looking for any excessive reduction in insulation resistance values at the higher voltage levels. Insulation that is thoroughly dry, clean, and without physical damage should provide roughly the same resistance values despite changes in test voltage levels. If resistance values decrease substantially when tested at higher voltage levels, this should serve as a warning that insulation quality may be deteriorating due to dirt, moisture, cracking, aging, etc.

$$\text{Polarization Index (PI)} = \frac{\text{10-minute reading}}{\text{1-minute reading}}$$

The IEEE Std 43-2000 lists the following minimum values for the polarization index for AC and DC rotating machines:

Class A: 1.5 Class B: 2.0 Class C: 2.0

Absorption curve of test conducted on 350 HP Motor: Curve D indicates a good insulation with an excellent polarization index of 5. Curve E indicates a potential problem. The polarization index is only 140/95, or 1.47.

(2) IEEE Std. 43-2000, "Recommended Practice for Testing Insulation Resistance of Rotating Machinery." Available from the Institute of Electrical and Electronics Engineers, Inc., 345 E. 47th St., New York, NY 10017.

BEFORE AND AFTER REPAIR:

Curve F shows a downward trend of insulation resistance values as the test voltage is increased. This indicates a potential problem with the insulation. Curve G shows the same equipment after it has been repaired.

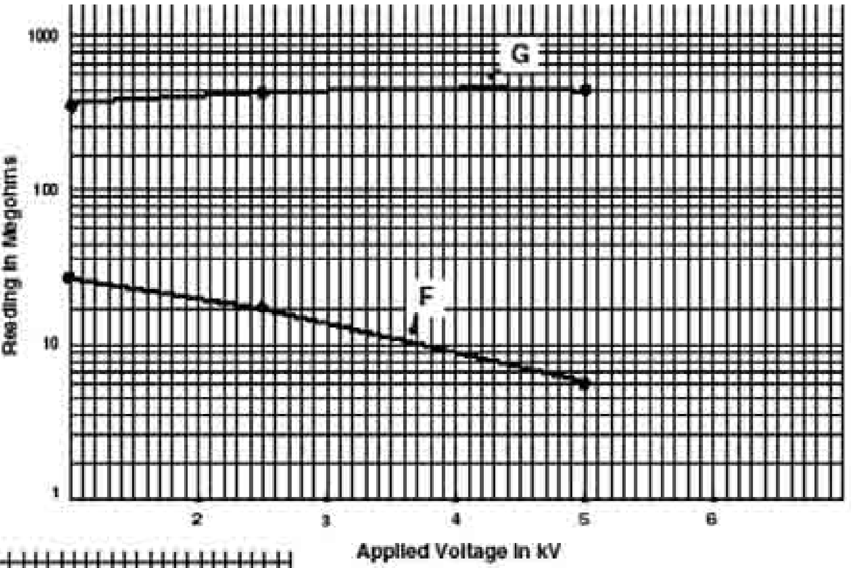
UTILIZING THE GUARD TERMINAL

The guard terminal is useful when measuring very high resistance values.

WHAT TEST VOLTAGE SHOULD I USE?

There are two schools of thought regarding the voltage to test insulation at. The first applies to new equipment or cable and can use AC or DC test voltages.

When AC voltage is used, the rule of thumb is 2 x nameplate voltage + 1000. When DC voltage is used (most common on megohmmeters manufactured today) the rule of thumb is simply 2 x nameplate voltage except when higher voltages are used. See chart below for suggested values.



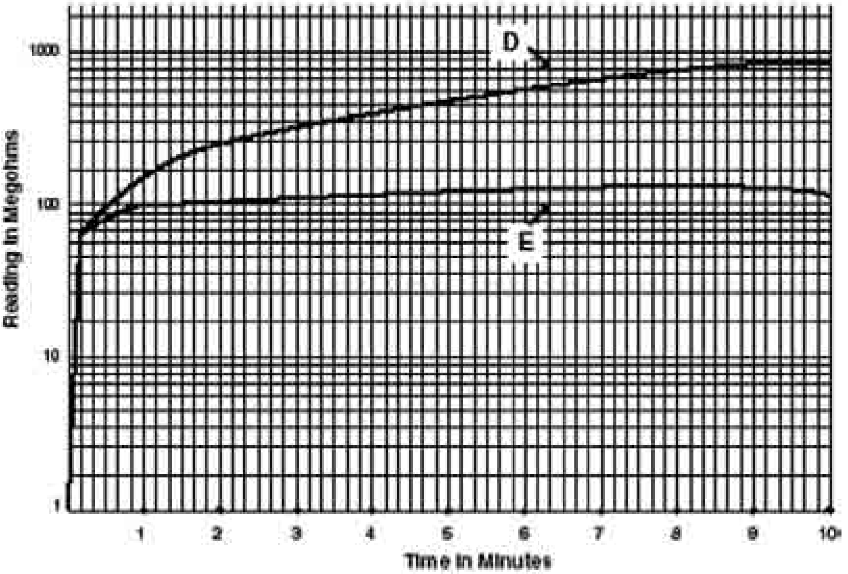


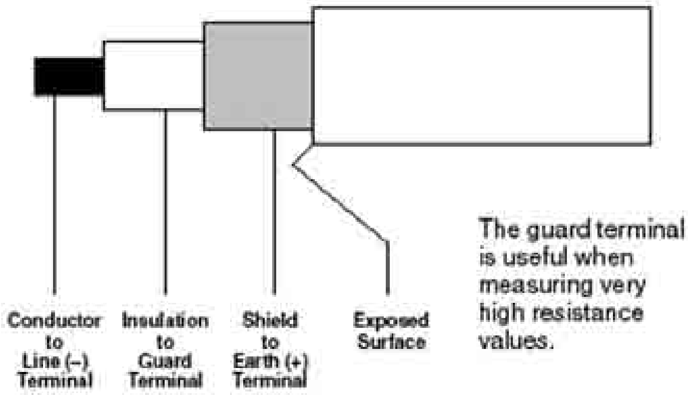
Figure 2

EQUIPMENT/CABLE RATING

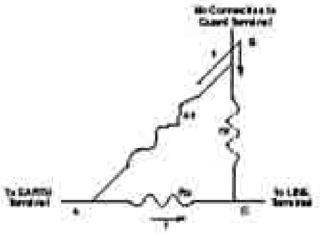
24 to 50V
50 to 100V
100 to 240V
440 to 550V
2400V
4100V

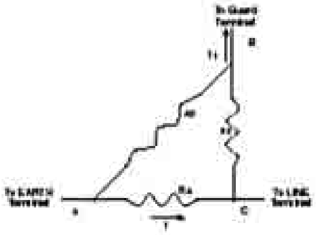
DC Test Voltage
50 to 100VDC
100 to 250VDC
250 to 500VDC
500 to 1000VDC
1000 to 2500VDC
1000 to 5000VDC

It is always advisable to contact the original equipment manufacturer to get their recommendation for the proper voltage to use when testing their equipment.


Conductor to Line (–) Terminal
Insulation to Guard Terminal
Shield to Earth (+) Terminal
Exposed Surface

The guard terminal is useful when measuring very high resistance values.





ADVANTAGES OF DC TESTING

- Lighter size and weight of test equipment
- Non-destructive
- Historical data can be compiled

TRANSFORMER TESTING

Transformers are tested at or above the rated voltage to be certain there are no excessive leakage paths to ground or between windings. These are conducted with the transformer completely disconnected from the line and load. However, the case ground should not be removed.

SINGLE-PHASE TRANSFORMER

The following 5 tests and corresponding wiring diagrams will completely test a single-phase transformer. Allow at least 1 minute for each test or until the reading stabilizes.

a. High voltage winding to low voltage winding and ground

b. Low voltage winding to high voltage winding and ground

c. High voltage winding to low voltage winding

d. High voltage winding to ground

e. Low voltage winding to ground

THREE-PHASE TRANSFORMER

The following 5 tests and corresponding wiring diagrams will completely test a three-phase transformer.

a. High voltage winding to low voltage winding and ground

b. High voltage winding to ground with low voltage winding to guard

c. High voltage winding to low voltage winding

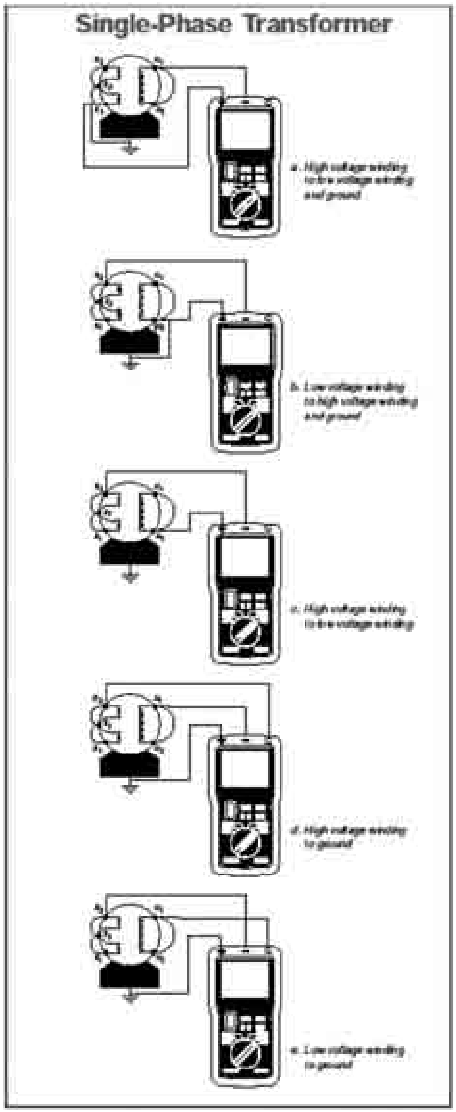
d. Low voltage winding to ground and high voltage winding to guard

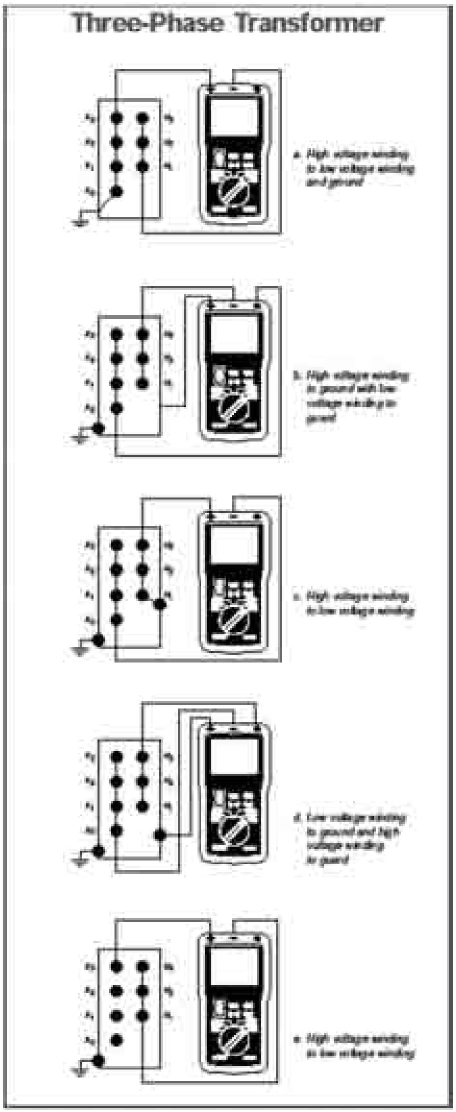
e. High voltage winding to low voltage winding

+ = *Earth Terminal* **−** = *Line Terminal* **G** = *Guard Terminal*

CABLE TESTING

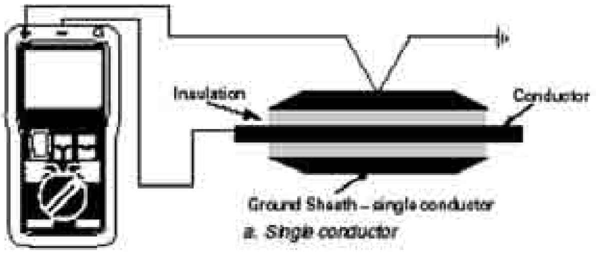
Transformers are tested at or above the rated voltage to be certain there are no excessive leakage paths to ground or between windings. These are conducted with the transformer completely disconnected from the line and load. However, the case ground should not be removed.


Single-Phase Transformer
a. High voltage winding to low voltage winding and ground
b. Low voltage winding to high voltage winding and ground
c. High voltage winding to low voltage winding
d. High voltage winding to ground
e. Low voltage winding to ground

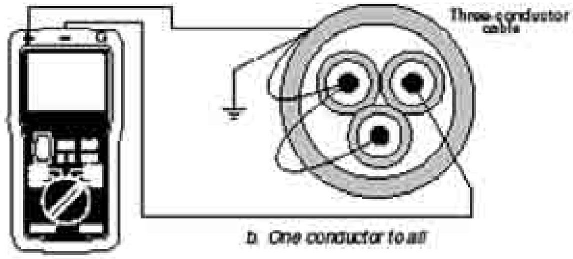

Three-Phase Transformer
a. High voltage winding to low voltage winding and ground
b. High voltage winding to ground with low voltage winding to guard
c. High voltage winding to low voltage winding
d. Low voltage winding to ground and high voltage winding to guard
e. High voltage winding to low voltage winding

SINGLE CONDUCTOR

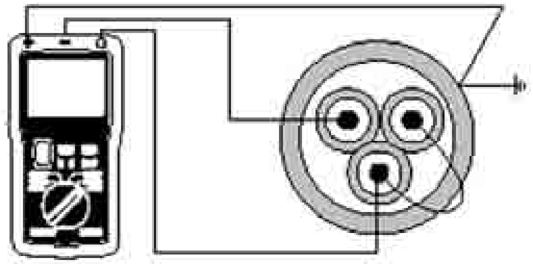
Connect as shown in the diagram
a. Conductor to Line (-) terminal and sheath to Earth (+)
Multi-Conductor
a. Single conductor
b. One conductor to all
c. One conductor to earth
d. One conductor to others minus ground



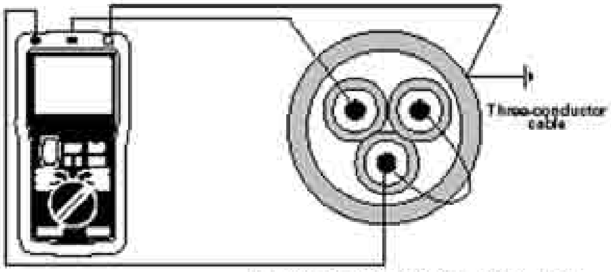
a. Single conductor



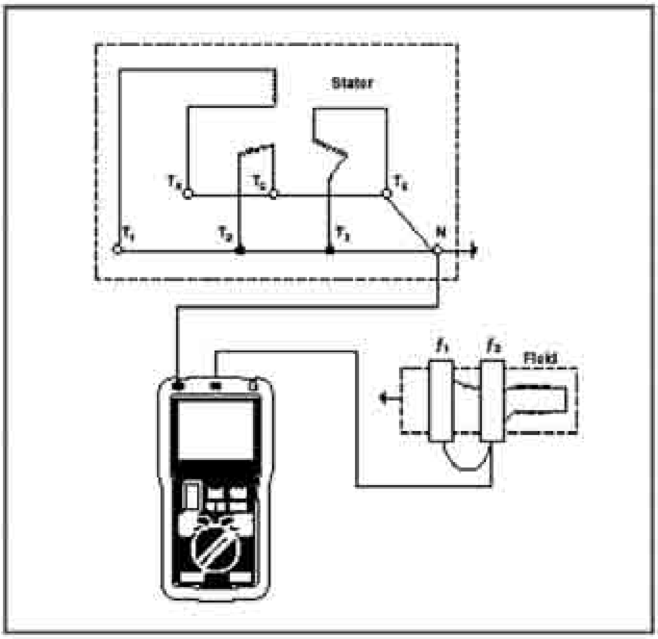
b. One conductor to all



c. One conductor to earth



d. One conductor to others minus ground



+ = Earth Terminal — = Line Terminal G = Guard Terminal

MOTOR AND GENERATOR TESTING

Before testing the above, lift the rotor brushes, ground the starter terminal and frame and ground the motor shaft. Discharge the field winding by grounding, then remove the field winding from ground and connect to the (-) Line connection on the megohmmeter. Connect the (+) Earth terminal to ground. The diagram shows the connection for testing the field insulation resistance. The stator winding may also be measured in a similar manner.

WHY CALIBRATE TEST EQUIPMENT?

Fluke Corporation

You're serious about your electrical test instruments. You buy top brands, and you expect them to be accurate. You know some people send their digital instruments to a metrology lab for calibration, and you wonder why. After all, these are all electronic — there's no meter movement to go out of balance. What do those calibration folks do, anyhow — just change the battery?

These are valid concerns, especially since you can't use your instrument while it's out for calibration. But, let's consider some other valid concerns. For example, what if an event rendered your instrument less accurate, or maybe even unsafe? What if you are working with tight tolerances, and accurate measurement is key to proper operation of expensive processes or safety systems? What if you are trending data for maintenance purposes, and two meters used for the same measurement significantly disagree?

WHAT IS CALIBRATION?

Many people do a field comparison check of two meters, and call them "calibrated" if they give the same reading. This isn't calibration. It's simply a field check. It can show you if there's a problem, but it can't show you which meter is right. If both meters are out of calibration by the same amount and in the same direction, it won't show you anything. Nor will it show you any trending — you won't know your instrument is headed for an "out of cal" condition.

For an effective calibration, the calibration standard must be more accurate than the instrument under test. Most of us have a microwave oven or other appliance that displays the time in hours and minutes. Most of us live in places where we change the clocks at least twice a year, plus again after a power outage. When you set the time on that appliance, what do you use as your reference timepiece? Do you use a clock that displays seconds? You probably set the time on the "digitschallenged" appliance when the reference clock is at the "top" of a minute (e.g., zero seconds). A metrology lab follows the same philosophy. They see how closely your "whole minutes" track the correct number of seconds. And they do this at multiple points on the measurement scales.

Calibration typically requires a standard that has at least 10 times the accuracy of the instrument under test. Otherwise, you are calibrating within overlapping tolerances and the tolerances of your standard render an "in cal" instrument "out of cal" or vice-versa. Let's look at how that works.

Two instruments, A and B, measure 100V within 1%. At 480V, both are within tolerance. At 100V input, A reads 99.1V and B reads 100.9V. But if you use B as your standard, A will appear to be out of tolerance. However, if B is accurate to 0.1%, then the most B will read at 100V is 100.1V. Now if you compare A to B, A is in tolerance. You can also see that A is at the low end of the tolerance range. Modifying A to bring that reading up will presumably keep A from giving a false reading as it experiences normal drift between calibrations.

Calibration, in its purest sense, is the comparison of an instrument to a known standard. Proper calibration involves use of a NIST-traceable standard — one that has paperwork showing it compares correctly to a chain of standards going back to a master standard maintained by the National Institute of Standards and Technology.

In practice, calibration includes correction. Usually when you send an instrument for calibration, you authorize repair to bring the instrument back into calibration if it was "out of cal". You'll get a report showing how far out of calibration the instrument was before, and how far out it is after. In the minutes and seconds scenario, you'd find the calibration error required a correction to keep the device "dead on", but the error was well within the tolerances required for the measurements you made since the last calibration.

If the report shows gross calibration errors, you may need to go back to the work you did with that instrument and take new measurements until no errors are evident. You would start with the latest measurements and work your way toward the earliest ones. In nuclear safety-related work, you would have to redo all the measurements made since the previous calibration.

CAUSES OF CALIBRATION PROBLEMS

What knocks a digital instrument "out of cal"? First, the major components of test instruments (e.g., voltage references, input dividers, current shunts) can simply shift over time. This shifting is minor and usually harmless if you keep a good calibration schedule, and this shifting is typically what calibration finds and corrects.

But, suppose you drop a current clamp — hard. How do you know that clamp will accurately measure, now? You don't. It may well have gross calibration errors. Similarly, exposing a DMM to an overload can throw it off. Some people think this has little effect, because the inputs are fused or breaker-protected. But, those protection devices may not trip on a transient. Also, a large enough voltage input can jump across the input protection device entirely. This is far less likely with higher quality DMMs, which is one reason they are more cost-effective than the less expensive imports.

CALIBRATION FREQUENCY

The question isn't whether to calibrate — we can see that's a given. The question is when to calibrate. There is no "one size fits all" answer. Consider these calibration frequencies:

- Manufacturer-recommended calibration interval. Manufacturers' specifications will indicate how often to calibrate their tools, but critical measurements may require different intervals.

- Before a major critical measuring project. Suppose you are taking a plant down for testing that requires highly accurate measurements. Decide which instruments you will use for that testing. Send them out for calibration, then “lock them down” in storage so they are unused before that test.
- After a major critical measuring project. If you reserved calibrated test instruments for a particular testing operation, send that same equipment for calibration after the testing. When the calibration results come back, you will know whether you can consider that testing complete and reliable.
- After an event. If your instrument took a hit — something knocked out the internal overload or the unit absorbed a particularly sharp impact — send it out for calibration and have the safety integrity checked, as well.
- Per requirements. Some measurement jobs require calibrated, certified test equipment — regardless of the project size. Note that this requirement may not be explicitly stated but simply expected — review the specs before the test.
- Monthly, quarterly, or semiannually. If you do mostly critical measurements and do them often, a shorter time span between calibrations means less chance of questionable test results.
- Annually. If you do a mix of critical and non-critical measurements, annual calibration tends to strike the right balance between prudence and cost.
- Biannually. If you seldom do critical measurements and don’t expose your meter to an event, calibration at long frequencies can be cost-effective.
- Never. If your work requires just gross voltage checks (e.g., “Yep, that’s 480V”), calibration seems like overkill. But what if your instrument is exposed to an event? Calibration allows you to use the instrument with confidence.

MAKING BETTER ELECTRIC FIELD MEASUREMENTS

Steve King

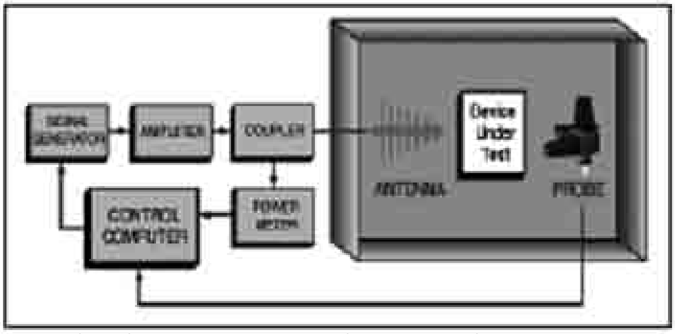
Electromagnetic field probes (field sensors) have become an indispensable tool for engineers performing EMC measurements and tests. First introduced commercially in the 1980s, they are now a common item in test labs worldwide.

The subject of this article is the factors involved in selection and use of the electric field (E-field) probes typically found in the feedback loops of immunity test setups, and anywhere else field strength values need to be measured.

UNDERSTANDING THE DIFFERENCE BETWEEN PROBES AND ANTENNAS

While, in a broad sense, probes can be thought of as antennas, they are different than most antennas in a number of aspects. Generally speaking, antennas are designed to transmit or receive electromagnetic signals or power with maximum coupling to the electromagnetic field. As a result, antennas typically perturb the electromagnetic field. Probes, on the other hand, are designed to measure the electromagnetic field with minimal field perturbation. To accomplish this, they should be as physically and electrically small as practical for the application, so coupling with the field of interest is minimized. E-field probes usually use an electrically small dipole coupled with a diode as a sensor. The diode and conditioning circuitry present a high impedance load to the probe's dipole, so little power is drawn from the received field. The combination of small size and a high impedance load minimizes the field perturbation.

While not in the scope of this article, it's also worth mentioning that trying to apply standard antenna calibration methods to field probes can produce inconsistent results. IEEE Standard 1309 [1] should be used as a reference for probe calibration methods.



Example of an E-field probe being used in the feed -back loop of an immunity test system.

ISOTROPIC PROBES

For most EMC test applications, isotropic (non directional) probes are the best choice. They provide more accurate measurement and are less critical about their orientation in the field of interest. This results from the geometry of their construction. Three independent broadband sensing elements are placed orthogonally to each another in an X, Y, Z configuration. Each element's output is measured, the vector sum is determined, and the result is the total field value.

A three-axis probe allows you additional flexibility. Ordinarily, you'll simply program the probe to calculate and send you RMS values and then use this measurement to control the field inside a test chamber. However, you can program the probe to send you readings from each of the three axes.

Using this data, you can then calculate field polarization as well as magnitude.

ISOTROPIC DEVIATION

Isotropic deviation (isotropy) is the specification that describes how well a probe measures field intensities irrespective of the polarization of the field, or the probe's orientation. Lower is better. The best probes typically have an isotropic deviation of 0.5 dB (which is a uniformity of 6%) or less.

Manufacturers typically specify isotropic deviation at a particular frequency, but this specification can be misleading, because the value given can be frequency dependent. Usually it increases (i.e., gets worse) as the frequency increases.

You can minimize the effect of isotropic deviation on your test if you know the specifics of your test setup and take measurements separately from each of the probe's sensing elements.

For example, if you know the polarization of the field, you can position the probe so that one of the elements is aligned with the field.

Measuring the field strength is then simply a matter of making a measurement from that element. The measurements from the other elements, which will be oriented perpendicular or end-on to the field, will tend to be very small and can usually be ignored.

DYNAMIC RANGE AND LINEARITY

Dynamic range is the maximum to minimum power level or field intensity that can be sensed by the probe over its specified frequency range.

Measurements are expressed in dB and represent a logarithmic power or voltage ratio. For example, a 10:1 field strength ratio is 20 dB. It's a good idea to check the manufacturer's specifications against your requirements and make sure you have some headroom to prevent inaccurate readings due to compression.

Linearity is a measure of how accurately the probe indicates actual values over its dynamic range.

Manufacturer's specifications of ± 0.5 dB are common. However, consider whether the specification is referencing the reading or the full scale. For example at 0.5 dB, if you're making a 1 V/m reading with a probe that has a 10 V/m range, and the linearity specification is referenced to the reading, then the maximum linearity error is 60 mV/m (6% of 1 V/m). On the other hand, if the specification is referenced to full scale, the linearity error is ten times that, or 600 mV/m.

FREQUENCY RESPONSE

A probe's response will not be perfectly flat across its entire frequency range.

To compensate for this, manufacturers provide calibration data for their probes. If the calibration contains many data points across the probe's frequency range, it will be easier to compensate for frequency variations with greater precision. However, if the calibration data provided is not sufficient for your application, you may have to pay extra to have the manufacturer (or a third party) generate a more detailed frequency response plot for your particular application. The calibration factors can often be entered into the control program and factored into the system measurement calculations.

An isotropic E field probe compared in size with a double ridged horn antenna. Probes should be electrically and physically small to minimize field perturbance.

RESPONSE TIME

Typical EMC susceptibility tests call for sweeping the test signal across a specified frequency band. Because E-field probes are used in the control loop to regulate the field intensity, their response time is a factor in how quickly you can sweep the test signal.

Probes used should be able to sample more than 50 times per second. Faster response time will save time and let you finish the test more quickly. At the highest sample rates (now in excess of 200 readings per second) the limiting factor may be the ability of the readout device or computer to accept and process the data.

Of course, probe response time is not the only factor determining how fast you can sweep the test frequency.

Other factors include the settling time of the signal generators and amplifiers you use to generate the field. Take all of these factors into account when writing a test program to ensure that the field is stable before performing tests.

If your application includes mode stirred testing in a reverberation chamber, sampling speeds greater than 50 times per second will be required.

The reason is that you are not simply controlling the field, but also collecting data to verify that the field inside the chamber has the appropriate distribution of field strengths and approach angles. The faster you collect this data, the faster you can make this verification, and the shorter your test time will be. Fast probes with sampling speeds exceeding 200 samples per second should be considered for mode stirred testing.

MEASUREMENT RANGE

For some applications, it's important to use a probe with a single measurement range. In an environment with a constantly fluctuating field (such as a reverb chamber) changing ranges can be time consuming or impossible.

Range changing effectively reduces the probe's sample rate. If the length of the test is dependent on the sample rate of the probe, and significant range switching is involved, test times will increase.

READOUTS

Probe signal conditioning, control and monitoring functions and system interface can be accomplished by connecting with a personal computer or dedicated probe controller. Each method has its advantages.

A dedicated probe controller usually manages the functions of one or more probes, and provides a GPIB (or other) interface port. The advantage of a dedicated controller is that the probes can continue to function even if the test system's computer is down or unavailable. Another advantage is that the probes can be isolated from the rest of the equipment – a help when troubleshooting problems. If you plan on using a dedicated controller, check to see that it can support the number and types of probe you plan to use, that it provides test system I/O using accepted conventions (i.e. GPIB, etc.), and that any software required is documented and supported.

You may also choose to use a desktop PC or laptop computer as your probe controller. Make sure the computer you choose is sufficiently robust to process and store input from one or more of the type of probes you intend to connect.

Bus speed will be important and should exceed the data transfer rate of your probes. This applies to the computer's input ports (i.e. serial, USB) as well.

Some probe manufacturers supply PC compatible software for their probes as well as drivers for GPIB, LabVIEW, etc. Check to be sure documentation and support are provided.

POWER SOURCE

Most E-field probes use batteries as their power source. The typical operating life of these batteries (before recharging or replacing) is approximately 8-10 hours. If your test exceeds that time frame, you'll need to recharge or swap your probe's batteries.

This can become inconvenient for long duration tests, or if there are multiple probes located in out-of-the-way locations such as chamber ceilings, motor bay cavities, etc.

To overcome these disadvantages, probes with external laser-driven power sources have been recently introduced.

In laser-powered probes, laser light is piped from a laser source through fiber optic cable to the probe where it is converted to electric power. While this technology is not entirely new, its application as a power source for E-field probes is. The advantage is that measurements can be made continuously without interruption, for a virtually unlimited length of time.

The power sources for some laser-powered probes are physically large and require AC power. However, one manufacturer has introduced a unit that is not much larger than an iPod and draws its power from the USB port of a PC. This makes remote field measurements using only a laptop PC, a practical possibility.

With current technology, laser powered field probes can be placed up to 100 meters from the power source.

Replacing batteries with laser light as a power source overcomes replacement and recharging issues, and allows testing to be performed over extended periods of time. The laser power sources are small and draw power from a PC USB port.

SIZE MATTERS

Small probes will perturb fields less than larger ones. A probe will begin to perturb fields when the dimensions of its housing approach ? wavelength of the frequency of interest. Some manufacturers have been able to miniaturize their probes by having the signal conditioning performed outside of the probe. If this is done properly, the size of the probe can be reduced without sacrificing accuracy.

Another benefit of miniaturization is the ability to place probes in small confined spaces like the interior of equipment enclosures, small TEM Cells or bench top RF isolation cells.

CONCLUSION

We've addressed a number of the factors involved in the selection, evaluation, comparison, and use of Efield probes. This survey is not exhaustive, but should provide a good basis on which to select, evaluate, and use E-field probes.

REFERENCES

1. IEEE 1309-1996, "IEEE Standard for Calibration of Electromagnetic Field Sensors and Probes Excluding Antennas from 9 kHz to 40 GHz. 1996." Institute of Electrical and Electronics Engineers. Piscataway, NJ. 800-701-4333. www.ieee.org.

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OBTAINING MORE ACCURATE RESISTANCE MEASUREMENTS USING THE 6-WIRE OHMS MEASUREMENT TECHNIQUE

Thomas Schwertner, Applications Engineer, Keithley Instruments, Inc.

INTRODUCTION

The explosive growth in the computer, telecommunications, and automotive electronics industries continues to drive efforts to minimize component size and speed high-volume production. This is placing similar demands on component manufacturers. In the resistive devices market segment, discrete resistors continue to maintain a strong position, but resistor networks are growing rapidly because they offer high functionality while conserving precious PC board space.

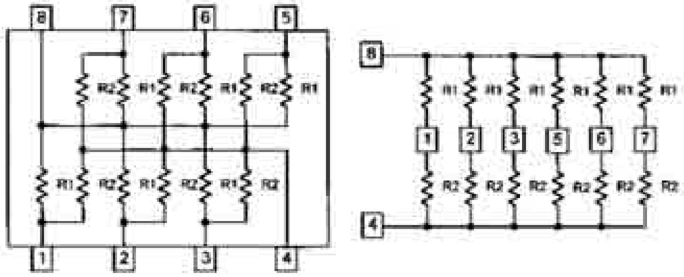


Figure 1: An 8-pin dual-terminator network and its electrical equivalent.

Manufacturers of resistors and resistor networks are being asked to increase their productivity, while maintaining guaranteed component accuracies. To meet these goals, resistance measurements must be performed in various stages of production as quickly as possible.

Among the most troublesome problems manufacturers encounter in electrical testing of resistors and resistor networks are the measurement errors caused by parallel resistance paths. Major sources of these errors include:

- Adjacent resistive elements in a network, and
- Contamination of the test probes and fixturing.

Either of these problems can lead to poorer product quality, lower yields, and ultimately, reduced manufacturer profitability. This paper offers an overview of these measurement problems and describes how the 6-wire ohms technique electrically eliminates these fundamental sources of error.

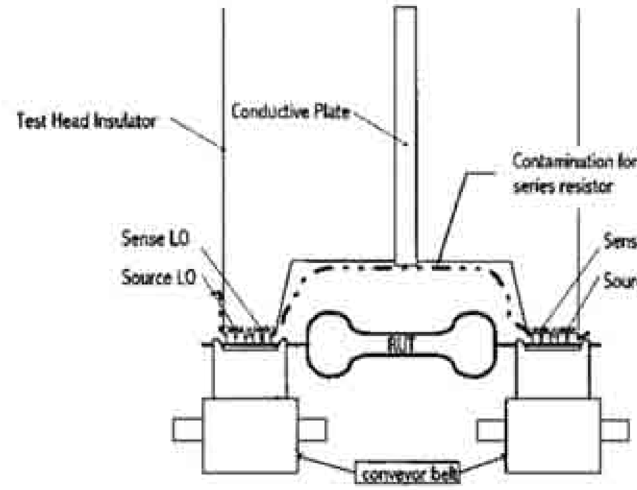


Figure 2: Axial resistor handler

PARALLEL RESISTANCE PATHS CAUSED BY ADJACENT RESISTIVE ELEMENTS

This problem occurs most frequently for manufacturers of "dual terminator" networks used for SCSI terminator applications, high-frequency attenuators used in RF communications, and impedance-matching circuits. In these types of components, the resistive element under test is shunted by other resistive elements, creating a "delta" or "loop" configuration. With ordinary test methods, a significant part of the test current will flow through all the other elements, producing a lower resistance reading than the actual resistance value. In most cases, it is not possible or desirable to break the loop physically in order to measure the individual resistive elements.

An 8-pin dual-terminator resistor network (Figure 1) will be used to illustrate this problem. Each resistor in this network is connected to a series resistor and to several series resistor loops in parallel. The electrical equivalent is a group of delta circuits (Figure 1, right.) Because of the effects of shunting resistances, the apparent value of adjacent resistors will be less than the resistance of each individual resistor element when using conventional measurement techniques.

PARALLEL RESISTIVE PATHS CAUSED BY CONTAMINATED TEST FIXTURING

This type of measurement problem is most common for manufacturers of high volume resistors and resistive devices that require precision tolerances. Typically, these resistive devices are assembled, labeled and tested using a high-speed handler. Over time, the lubricants used on the moving parts of the handler and other processing equipment become dispersed to many areas of the production floor, including the test fixturing. This contamination causes resistive paths to form across the resistor under test.

Figure 2 illustrates this problem, using an axial resistor handler as an example. These types of handlers offer through-puts of more than 20,000 parts/hour.

Over time, the dispersed lubricants will cause a conductive film to build up across the two sides of the test heads probes, forming a bridge resistor. Eventually, the resistive value of this resistor in series could go as high as 100,000Ω. When measuring a 10,000Ω resistor, this would result in an additional error of about 9%.

One way to eliminate the problem is to clean the test fixture frequently on a regular schedule. However, frequent cleaning cycles may lead to excessive downtime and lower productivity. An alternative would be to use a guarded text fixture. Guarding is achieved by splitting the insulator between the LO and HI side of the probes of the test head and placing a conductive layer in between. This will electrically split the series resistor built by the contamination into two series resistors. The equivalent electrical model is equal to a three resistor delta configuration, similar to that shown in Figure 3. Once this is done, the guarded ohm technique can be employed to eliminate electrically the error caused by the contamination. This permits the use of longer cleaning cycles and helps maintains the productivity of the test stand.

APPLYING THE 6-WIRE OHMS TECHNIQUE TO SOLVE SHUNTING RESISTANCE MEASUREMENT PROBLEMS

The 6-wire ohms technique builds upon the industry-standard 4-wire ohms measurement technique, enhancing its performance in these applications by eliminating the effects of any shunt resistance. Creating a 6-wire ohmmeter involves adding a low impedance guard buffer with sufficient drive current to a 4-wire ohmmeter.

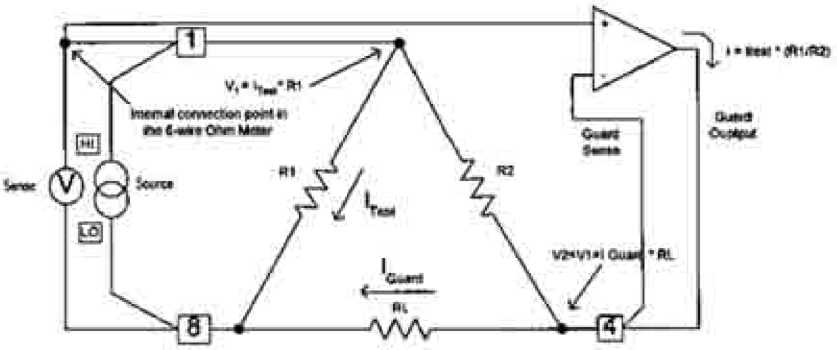


Figure 3: Equivalent circuit when measuring R1 of the dual-terminator shown in Figure 1.

As noted previously, both the cases described have a similar electrical equivalent, a circuit where three resistive elements are being connected in a triangular fashion.

Figure 3 shows the electrical equivalent circuit when measuring resistor element R1 of the resistor network device shown in Figure 1. Related to the resistive path caused by contamination, R1 would be the resistor under test (RUT), while R2 and RL would be the resistive equivalent of the contaminating film in Figure 2.

The solution to this measurement problem is to "guard out" the parallel resistance electrically by forcing the voltage on the middle point of the two bridging resistors (R2 and RL) to the same potential as Source HI. No more current will flow through the series-parallel loop. The 6-wire ohmmeter guard buffer accomplishes this by forcing current through RL.

From a technical perspective, the 6-wire ohmmeter guard buffer is a unity-gain amplifier (op-amp) with a shunt resistor across the input, which will hold the voltage between its inputs and therefore, across the resistor (R2 in Figure 3), to nearly 0V. In the technical literature, this technique is sometimes also referred to as a "voltage follower" technique.

The level of current the Guard Output has to provide in order to guard out the series resistance built up in an automatic component handler's test heads, e.g., for axial resistors (Figure 2) is fairly low, probably on the order of 0.5mA in the worst case. For networks with adjacent resistor loops, however, it might go as high as 50mA. At this current level, any lead resistance (the sum of cable, contact, and switch relay resistance) will cause a voltage drop, resulting in an additional error. To compensate for it, the Guard Sense terminal, which is essentially the inverting input of the amplifier, has to be connected to the same point as Guard Output.

To summarize, a 6-wire ohmmeter takes advantage of an operational amplifier technique, the unity-gain circuit. With the provision of sufficient drive current, electrical guarding attains isolation of the resistor element under test, allowing for more precise measurements.

PRACTICAL ASPECTS AND LIMITS OF GUARD BUFFER CIRCUITRY

Traditionally, in electronics design, tradeoffs must be made between stability, speed, offset, and noise. Together, the sum of these tradeoffs determines the final accuracy of the instrument for a particular application. The guard buffer is no exception. The following discussion will deal with tradeoffs and errors the user must take into consideration when using the guarded ohms technique.

GUARD BUFFER OFFSET

An ideal operational amplifier will hold the voltage between the inputs to zero.

However, with commercially-available op-amps, a small offset voltage always remains, which may range from a few microvolts to hundreds of microvolts. The small offset voltage generates a current through the resistor (R2 in Figure 3) between Guard Output and Sense HI. This current subtracts from the sourced or measured current and produces an error. The error can be calculated as:

error = [Voffset /(R · Itest)] ? 100%

R is the resistor between Guard Output and Sense HI (R2 in Figure 3)

Itest is the measured or sourced current through the RUT

The formula shows that as R decreases, the error increases, whereas the error decreases as the test current increases. Two examples illustrating the use of this formula follow. One example calculates the additional error for a 180/390 dual terminator, while the other calculates the additional error contributed by the guard buffer for a 2MΩ axial resistor.

Example 1

The resistor under test is 390Ω, R = 180Ω and the test current 1mA. Assuming a 20?V offset voltage, the error = 0.011%.

Example 2

The resistance due to contamination is assumed to be 100kΩ and a test current is 10?A. Assuming a 20?V offset voltage, the error = 0.002%.

The above calculations show that the contributing error is directly proportional to the offset error of the guard buffer and inversely proportional to the shunt resistor between Guard Output and Sense HI. With the error in Example 1, a part with a specified tolerance as tight as 0.1% can be tested with good accuracy, while in Example 2, a part with 0.01% is still testable with sufficient accuracy. This assumes that the measure circuit does not contribute significantly to the error. Note: Always consider the guard error contribution to the total system error.

NOISE AND STABILITY

Any circuitry added to a measurement system will invariably add some noise. This is especially significant in applications where high measurement rates (A/D integration rates lower than the line cycle frequency) are important, because additional circuitry will contribute to some degree to the measurement uncertainty.

When designing a guard buffer circuit, a bipolar op-amp would be a desirable choice in order to minimize the noise. However, in a test system environment, the problem is that cable lengths of six feet or more are common. Under this circumstance, bipolar amplifiers tend to oscillate, which would cause an equivalent DC component which, in turn, will cause a significant error. To avoid this problem, a chopper-stabilized amplifier should be used for additional system stability, even though it will contribute additional noise.

System noise is especially a problem in applications where higher repeatability is required. Modern 6-wire ohmmeters allow users to adjust the measurement speed in multiples of the line cycle, and also offer digital filtering. These features make it possible for users to find the right measurement tradeoffs for applications where higher repeatability is critical.

INPUT BIAS CURRENT AND COMMON MODE REJECTION

The 6-wire ohmmeter must have a fairly high input impedance (e.g., >1010Ω) in order to provide good 4-wire resistance performance, particularly in applications where significant lead resistance is expected. The non-inverting input of the guard buffer is connected to the Sense HI line and, therefore, adds to the input impedance. For this reason, an op-amp with an input impedance of >1011Ω should be chosen.

In applications where precision measurements are required, the common mode rejection ratio (CMRR) of the amplifier becomes critical. In the case of the guard buffer circuit, a common mode voltage error will add to the guard buffer offset voltage, which will increase the total error. Assuming a 80dB CMRR and a 2V signal level, the additional voltage error would be 200?V. With 100dB CMRR, the voltage error would be 20?V. Therefore, it’s desirable to choose an op-amp with a CMRR greater than 100dB.

GUARD OUTPUT CURRENT

Operational amplifiers that can be used for designing a guard buffer typically have no more than 2mA output drive capacity. In general, this is enough to guard out any resistance due to contamination on a component test head.

In fact, this technique is widely used in low current applications such as leakage measurements.

Electrometers and current sources usually provide a terminal for the xl buffer with drive currents up to 2mA. Even some precision multimeters offer a Guard Output. Guard

Sense usually is not available on these meters. (See Ref. 1 for information on a test configuration and instrument that makes all of these connections available.)

Nevertheless, to provide a production test solution for parts like the dual terminator network in Figure 1, the drive current provided must be significantly higher. The load resistor between Guard Output and Source LO can go as low as 20Ω. Given that relatively high voltage noise levels are inherent in a factory floor environment, it is desirable to adjust the source signals at the highest possible level. The voltage across the load resistor is the same as that across the RUT. Assuming a voltage of 0.5V and a 20Ω load resistor, the guard buffer has to deliver a 25mA guard current. To obtain this level of current, a booster stage must be added to the guard buffer. This booster stage is essentially a transistor stage, designed to increase the level of the guard drive to about 50mA .

PROTECTION AND OVERLOADING

In essence, the guard buffer is an amplifier with a booster stage, thus creating a voltage source with a remote sense line. In additional to preventing oscillation, it is good practice to protect the guard buffer against overloading, electrostatic shock, and fly-back voltages.

It is not uncommon for measure leads to get shorted or for a programming mistake to close a switch at the scanning mainframe, which produces a short, especially during the design phase of a measurement system. Electrostatic loads and voltage peaks are very common on a production floor, especially when long cables and switching systems are involved.

To protect the guard buffer against shorts due to these problems, a series resistor and a fuse (preferably a thermal fuse) can be used. Peak voltage can be covered with protection diodes. The inverting input of the amplifier can be protected with a high value series resistor.

CONNECTION POINTS OF THE GUARD BUFFER

Once the guard buffer is designed, it must be tied into the rest of the circuitry to create the 6-wire ohmmeter. Figure 3 illustrates the connections that must be made. The non-inverting input of the amplifier connects to the Sense HI lead, which is virtually current free.

Connecting it to the Source HI Output would cause errors due to the voltage drop in printed circuit traces or elsewhere. The guard buffer ground reference connects to Source LO Output to provide the current return path for the amplifier. It does not connect to Sense LO, because the sense lines have to be held at zero amps.

LIMITS ON GUARDED OHMS MEASUREMENTS

At certain resistor ratios, there are some limitations on the use of the 6-wire ohms technique. Essentially, the theories of operational amplifier design apply, but there are two general limits. One limit is caused by the value of the Rshunt resistor between Guard Output and Sense HI and the other by the ratio of the load resistor (Rload) between Guard Output and Source LO and the RUT.

When Rshunt approaches very low values, two things happen. First, the current caused by the offset voltage causes a high error. Second, positive feedback may occur. This positive feedback means that noise will be amplified and back-coupled into the circuit, causing an additional error. Also, additional settling time will be required. This is particularly true if the ohmmeter uses a constant current measurement method.

When the ratio between RUT and Rload becomes very high (e.g., 1000:1), the guard current drive capacity provided by a single booster stage might not be sufficient to drive enough current through Rload. It is possible to furnish a second booster stage in order to provide more current capacity for the guard buffer, but the component can only tolerate a limited amount of power. If the power becomes too high, the RUT will overheat and be damaged.

SPECIAL CONSIDERATIONS FOR PRODUCTION TESTING

In general, two resistance measurement techniques can be used: constant current or constant voltage. Modern resistance measurement instruments like digital multimeters use the constant current method, while the constant voltage method usually is used in meters capable of measuring resistances of 108Ω and higher. The following provides a brief description of both techniques and shows how the constant voltage method increases production throughput, while the constant current method allows achieving maximum accuracy.

THE CONSTANT CURRENT METHOD

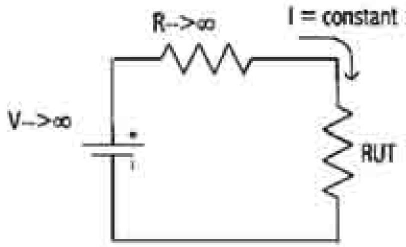


Figure 4: Equivalent current source circuit

The constant current method allows measuring resistances from fractions of an ohm to values as high as 1GΩ. In principle, a constant current source is a fixed level voltage source with a resistor of a high resistive value in series. An ideal current source has infinitely high output impedance.

In a typical digital multimeter (DMM), the voltage is usually derived from the precision reference that the meter needs for the analog-to-digital conversion. The value of the series resistor can be determined very accurately and stored as a calibration constant. Given that a typical DMM is supplied with five to seven ranges, this consequently offers a very precise method to measure resistance. Digital multimeters with better than 0.005% basic resistance accuracy are available.

THE CONSTANT VOLTAGE METHOD

The constant voltage method is traditionally used in very high resistance measurements. A variable voltage source up to 1000V is combined with a feedback ammeter to perform the measurement. An ideal voltage source has infinitely low output impedance. A feedback ammeter has virtually zero voltage burden across it.

However, it is possible and desirable to apply this method for measuring resistances of less than 100Ω. The lowest resistance range where this method is applicable is determined by the quality of the voltage source. Every voltage source has certain offsets. These offsets are temperature-dependent and usually stay constant in between subsequent measurements.

Assuming a voltage source with an offset of 600?V and a RUT of 10Ω, an error current of 60?A would flow. Unless the current meter allows suppressing this error current, this would equal a 0.06% error with a 1V test voltage. A suppression option can significantly improve the accuracy.

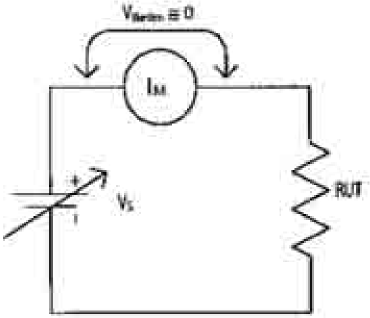


Figure 5: Ideal voltage source with ideal ampere meter

HOW TO CHOOSE BETWEEN THE METHODS

It may not be obvious why one would choose to use the constant voltage technique rather than the traditional constant current technique. However, the demands of high throughput production testing may add other considerations. In general, the issue can be divided into two categories: 1) applications with precision requirements and/or medium measure speed, and 2) applications with medium or low accuracy requirements but very high measurement speed.

In production test applications like testing precision wire-wound axial resistors or precision metal film resistors, the constant current technique is the best method, because it is possible using commercially available high-performance digital multimeters. These DMMs offer base accuracies of better than 0.01% at measurement speeds of 40 readings/second.

In applications like testing high volume dual terminator resistor networks, a 6-wire ohmmeter that uses the constant voltage technique is best. In this type of application, the measurement system is coupled with a switching system in a matrix configuration. The throughput is very critical — the time spent in testing adds an expense that is directly proportional to the cost of the part. With modern 6-wire ohmmeters, throughput times of less than 4ms per network element can be achieved, while maintaining an absolute accuracy of 0.1% and a repeatability of better than 0.01%.

HOW THE CONSTANT VOLTAGE METHOD IMPROVES THROUGHPUT

The constant voltage method offers significant throughput improvements over the constant current method by minimizing source and system settling times. The result is faster measurement cycles and, therefore, a higher parts per second ratio. In addition, sourcing voltage decreases the system's noise susceptibility at high reading rates.

To explore the details of how the constant voltage technique works, let's first discuss the influence of settling time, then the noise issues involved:

Reduced settling time. In any measurement system, certain delay times are inherent. The sum of the external cabling, switching systems, and common mode capacitance, which forms a parallel capacitance across the Source HI and Source LO outputs, also increases the required settling time. The capacitive value of this "apparent" capacitor might go as high as 5nF.

With the constant current method, the capacitor needs to be charged first, because it will appear initially as a virtual short.

It takes roughly seven times the time constant (RC) for the signal to settle to 0.1% of its final value. For example, assuming a 100kΩ resistor under test, a 10µA test current, and a 5nF apparent parallel capacitor, it would take about 3.5ms for the signal to settle ($t_{0.1} \approx 7 \cdot \tau$; $\tau = R \cdot C$; $V_{Final} = 1V$).

The guard buffer will follow the voltage apparent on the Sense HI but will also contribute additional settling time. With low R_{shunt} values, the guard will back-couple phase and level shifted voltage noise. Finally, at fast measurement rates, this will cause an additional error.

One solution would be to add another guard to the system, which would drive the Sense and Source HI shield. In a switching application with multiple elements, it would add significantly to the cost of the system. The better solution is to use the constant voltage method.

In sharp contrast to the constant current method, the settling time of a system using the constant voltage method is dependent on the slew rate of the voltage source. With slew rates on the order of 0.08V/µs, in principle, it would take 12.5µs to reach a 1V source value. In practice, the time is slightly longer.

Noise. In the constant current method, a source with very high theoretical output impedance is attempting to force a constant current through a resistance by varying the voltage across it in response to an error signal (noise). The guard buffer is attempting to control a voltage on the other end of R_{shunt} without regard to current flow through it. In situations where the RUT, R_{shunt}, and R_{load} become small in value ($R_{shunt} < 100\Omega$, $V_{guard}/R_{load} > 10mA$, and RUT < 500Ω), measurement noise will increase noticeably at subline frequency integration rates. The noise generated is a combination of periodic and random noise elements.

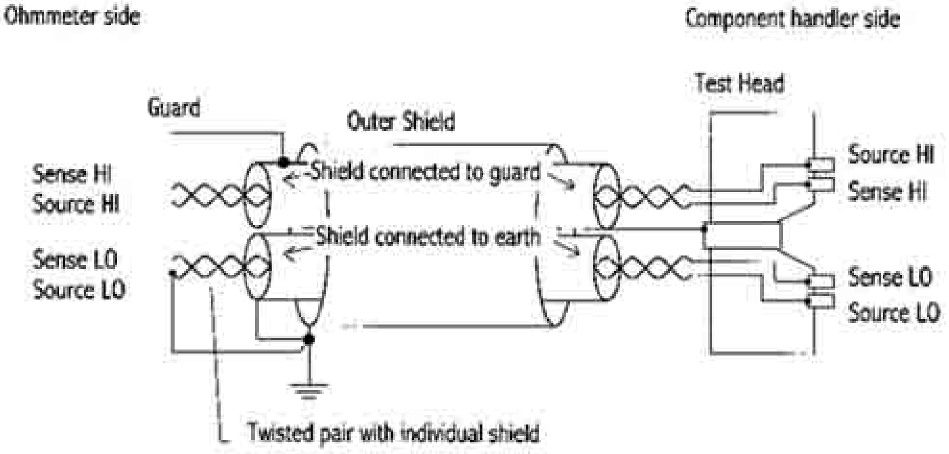


Figure 6: Proper connection scheme for axial or single chip resistors

By comparison, a constant voltage source with a low impedance output will clamp the voltage to the programmed value. The guard buffer follows to the same value minus its offset voltage. By choosing a source voltage well above the noise floor, the energy of the error signal will not, in general, be sufficient to contribute significantly to the current flowing though the RUT. Therefore, the constant voltage method will result in more accurate resistance measurements.

PRACTICAL ASPECTS OF BUILDING A TEST SYSTEM

The following section provides a practical overview on building a test system, particularly the wiring involved. In order to cover a wide resistance range, 4-wire connections are used. This section will focus on axial or chip resistors and resistor networks.

AXIAL OR CHIP RESISTORS

Making the correct connections to the handler test head is crucial to successful measurements using the guarded technique for single-resistor elements. The constant current method is used to ensure higher accuracy. Unlike measurements on resistor networks, no switching is involved in testing axial resistors, so only a single cable is needed. The best way to make the connection is to use a 7-conductor cable, one of which is a outer shield. The other six connectors are two sets of twisted pairs, with each pair surrounded by its own shield. The connections to the 6-wire ohmmeter are made in pairs of HIs and LOs. It is always desirable to pair wires with nearly the same potential, to minimize loading and leakage effects.

The shield around the Sense HI and Source HI pair is connected to the Guard Output. Guard Sense can be connected to Guard Output at the meter, because minimal current is flowing. The shield of the Sense LO and Source LO pair is connected to earth ground. The outer shield is also connected to earth ground at the same point. To avoid forming ground loops, do not connect the other end of the cable to the earth ground of the device handler.

A common mode voltage and a common mode capacitance exist between Source LO and earth ground. In areas like a manufacturing floor, where the earth ground changes potential at fairly high peaks, this can induce error signals. It is important to note that Source LO should also be connected to earth ground as shown in Figure 6 to avoid additional errors.

By connecting the guard to the shield around the HI pair, capacitive coupling and leakage between LO and earth are effectively avoided, thereby providing faster and more accurate measurements. Guard is also routed to the conductive plate of the test head or to the guard ring around the test probes.

RESISTOR NETWORK DEVICES

Resistor network devices contain multiple resistive elements that must be tested. In general, this involves the use of switching hardware, so the connection scheme is not as straightforward as that illustrated in Figure 6. Depending on the device and the application, large switching matrixes may be required. The following example for a 8-pin dual terminator device offers a glimpse of some of the connection issues involved.

To test the dual terminator device shown in Figure 1, the switching scheme must be able to connect three pairs of connections to each of the device pins. Source HI and Sense HI,

Source LO and Sense LO, as well as Guard Output and Guard Sense must be switched to the individual device pins. Figure 7 shows a solution that could handle an 8-pin dual terminator device as well as a wide variety of other devices.

In this configuration, the guard cannot be used to shield

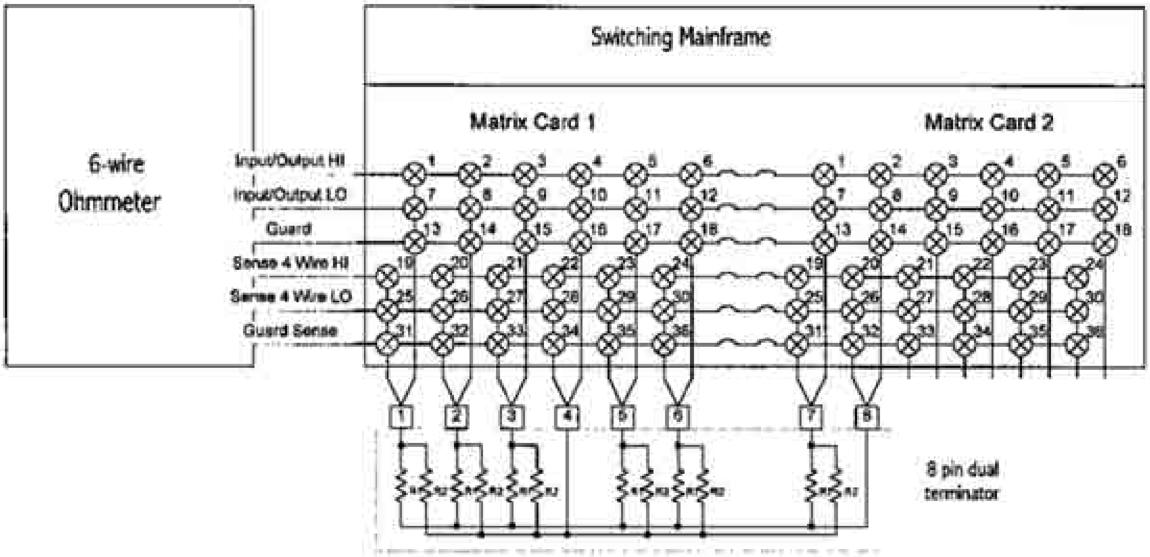


Figure 7: 6-wire Ohmmeter combined with a Switching Solution

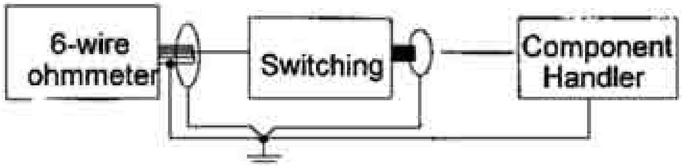


Figure 8: Shielding scheme for resistor network applications

the HI pairs. To provide proper shielding, choose a multiple-conductor cable with a good quality shield around it, like that shown in Figure 8. Through the use of the constant voltage method, parallel capacitance will not slow down the measurement. However, if resistances higher than 1M_ must be tested to very tight tolerances, use the wiring scheme shown in Figure 6 instead.

PRACTICAL SYSTEM SPEEDS AND ACCURACY CONSIDERATIONS

This discussion will conclude with a quick overview of system speed and how it will ultimately affect the parts per hour throughput.

SINGLE RESISTOR ELEMENTS

In situations where high volume precision parts are being tested and contamination may be causing error, the guarded measurement technique enables the ohmmeter to achieve its base accuracy. High performance ohmmeters, essentially precision digital multimeters, make it possible to attain high reading rates without sacrificing the meter's base accuracy substantially. The table shows the correlation between the meter's measurement speed and throughput, assuming the system uses an automated component handler capable of handling 50,000 devices per hour.

Measurement speed in ms	Base Accuracy	Devices/hour
25	0.0025%	37,113
8	0.005%	45,000
5	0.035%	46,753

RESISTOR NETWORK DEVICES

Resistor network devices require a combined switching and measurement solution, so the overall throughput achievable is very dependent on both of these factors. The following table provides an overview of different test solutions. The base accuracy obtained is 0.1% and the repeatability is better than 0.01%.

# of Elements/ Network	Measure and Binning (sec)	Data Transfer/ Handler (sec)	Total Time per Network (sec)	# of Networks/ Hour
8	0.004	0.1	0.132	27,273
8	0.012	0.1	0.196	18,367
8	0.020	0.1	0.260	13,846

CONCLUSION

The 6-wire ohms technique builds upon the industry-standard 4-wire ohms technique by adding a low impedance guard buffer to eliminate the effects of any shunt resistance causes by parallel resistance paths of the device under test and fixturing.

Integrating the guard buffer into a 4-wire ohms measurement instrument creates a "6-wire ohmmeter" and makes it possible to perform a variety of resistance measurements faster and more accurately than in the past.

In addition, allowing precise control of the current source and/or voltage source when measuring ohms enables the user to compensate for induced errors such as noise, system capacitance, lead resistance, and offsets. The Vsource ohms method is especially useful for minimizing settling times and, thus, increasing system throughput.

These two measurement considerations are especially critical in the production of resistor networks and precision resistors, and should be considered when choosing a measurement instrument.

HOW STRAY VOLTAGE AFFECTS MULTIMETER MEASUREMENTS

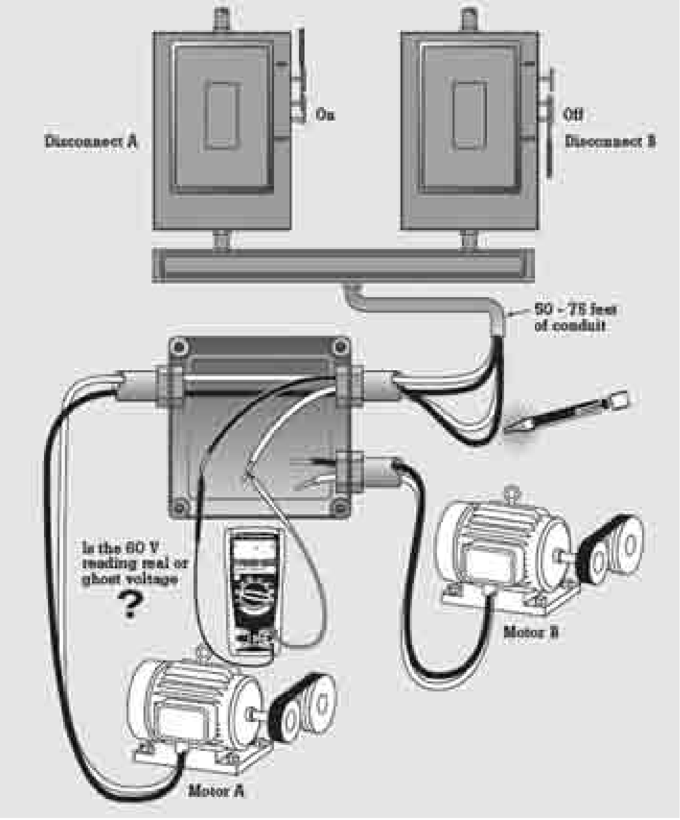
Fluke Corporation

For most electrical measurements in the industrial environment, a high impedance digital multimeter or electrical tester is the appropriate tool. These test instruments have a relatively high-input impedance (>1 megohm), which means that when connected, they don't load the circuit under test. These test tools generally will not affect circuit operation or circuit measurements.

On the other hand, low impedance test instruments can seriously load down a circuit under test and, in some cases, can adversely affect circuit operation and circuit measurements. This can happen with sensitive control circuits or in many electronic circuits found within industrial machinery.

However, even with a high impedance multimeter, there's still one confusing measurement situation that can occur in facilities or manufacturing plants. It's called stray or ghost voltage, and it happens specifically when using a high impedance test instrument for day-to-day measurements.

Stray or ghost voltages occur from capacitive coupling between energized circuits and non-energized, non connected adjacent wiring. Because of this coupling effect and the multimeter's high impedance, it's not always possible to determine if the circuit under test is energized or de-energized, and this creates confusion for the person performing the test.



WHERE ARE STRAY VOLTAGES ENCOUNTERED?

The most common place to encounter stray voltage is in unused cable runs or electrical wiring in existing conduit. When facilities or buildings are built and wired, it's very common for electricians to pull extra wire through the conduit for future use.

These wires are typically left unconnected until needed, but are subject to capacitive coupling from the powered wires. Another example is an open ground or neutral on a 120 V branch circuit or in card cages where 120 volt control circuits are used to control assembly line or conveyor functions.

WHAT DOES STRAY VOLTAGE LOOK LIKE?

Generally, for most electrical measurements, a high impedance multimeter is the best tool, since you don't want the meter loading the circuit and affecting the circuit measurements. However, when dealing with capacitive coupling, a high impedance meter between ground or neutral to the unconnected cable or open connection will indicate some amount of voltage present. Typically this measured voltage reading may be as high as 50 % of the energized voltage in the same proximity.

Is this voltage real? Yes, it is, but it's a static voltage, containing no real energy or current flow. When it comes to determining whether a circuit or connection is energized, this stray voltage reading presents a real source of confusion. Is the connection really hot or not?

THE FLUKE TL225 STRAY VOLTAGE ADAPTER TEST LEAD SET

The Fluke Stray Voltage Adapter Test Lead Set is an accessory that allows a high impedance multimeter to measure circuits, connections, cables or connectors subject to stray voltages. The adapter provides a low impedance load to the measured circuit, desensitizing the meter to low energy, spurious sources of interference. If the measurement points are energized with a hard voltage, the meter will simply display the voltage reading. If the measurement points contain a stray or ghost voltage, the meter will read very close to zero volts, indicating the circuit or connection is not energized.

WARNING

The stray voltage adapter is designed to be used in conjunction with high impedance digital multimeters for measurements on power circuits, to help determine whether the circuit is energized or not. The adapter presents a 3 k load to the circuit under test and thus will dissipate any stray voltage present if the circuit is not energized.

This adapter should not be used on low voltage control circuits or anywhere where the circuit under test could be adversely affected by this low impedance load. The adapter is designed to handle continuously applied power system voltages without damage, however proper use of this adapter is for intermittent use to determine whether a circuit is energized or not.

SAMPLE MEASUREMENT SCENARIO

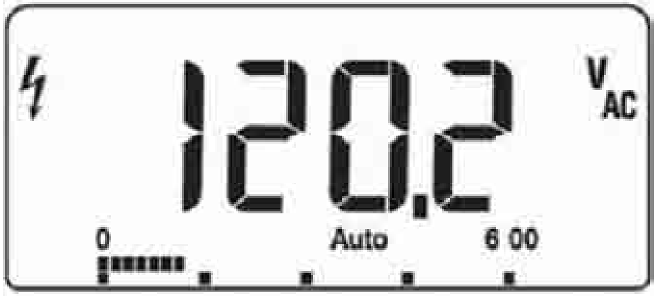


Figure A

Figure A is a normal reading for an energized 120 volt branch circuit between hot and neutral. This reading is displayed on the meter with or without using the stray voltage adapter.

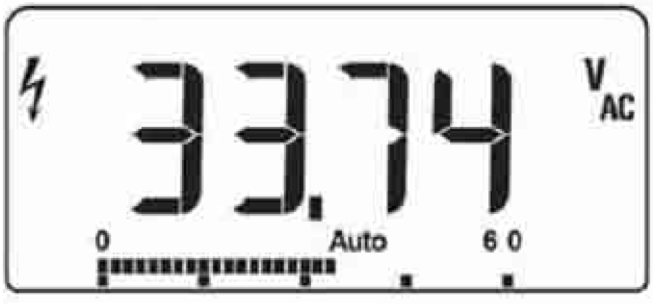


Figure B

Figure B is the measurement displayed with the high impedance DMM between neutral and an unconnected wire in the same conduit as a 120 volt branch circuit feed. Note the high impedance meter is displaying 33 volts. This is a capacitively coupled stray voltage reading.

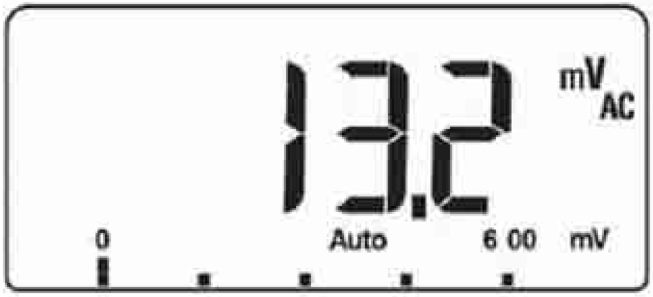


Figure C

Figure C is displaying the result of the measurement from Figure B when the stray voltage adapter is placed in the circuit. Note that the reading is now 13 millivolts or very close to zero volts, a non-energized connection.

The low impedance presented by the stray voltage adapter dissipates the stray voltage. If the reading in Figure B was a hard voltage, the reading in Figure C would have been the same reading as in Figure B.

SAFETY

Testing for stray voltage is a measurement typically made for a short period of time, such as less than a minute. The stray voltage eliminator module contained within the TL225 test lead kit is designed to withstand a continuous application of 1000 volts or less. The module has been tested to meet the IEC 1010-1 second edition CAT IV 600 V/CAT III 1000 V measurement category rating.

On a more personal safety note: If you've ever doubted your multimeter readings, consider the environment you're working in. Does it contain the ingredients for capacitive coupling? If it does, and if you need to rely on hot-or-not readings, you may want to consider adapting your multimeter. Stray voltage is confusing at best, and dangerous at worst. Don't be fooled!

REVISED ENGINEERING AND TESTING PRACTICES RESULTING FROM MIGRATION TO IEC 61850

Harold Fischer, Jeffrey Gilbert, and Greg Morton, PPL Electric Utilities Corporation; Michael Boughman and David Dolezilek, Schweitzer Engineering Laboratories, Inc.

Replacing hardwired connections with digital communications over Ethernet requires new engineering and testing practices. PPL Electric Utilities Corporation (PPL) recently designed, installed, and tested a new high-voltage substation using next-generation relay and control equipment.

This next-generation substation (NGS) is based on networked Ethernet intelligent electronic devices (IEDs) communicating via IEC 61850. This article discusses the new technical design details of networking IEDs over Ethernet, but also, and more importantly, it discusses how engineering, installation, and testing practices had to change to accommodate the new technology. PPL methodically replaced their previous protection and control design with a design that provides more functionality while migrating to IEC 61850 communications from multiple IED vendors.

In the end, over 50 percent of the hardware, 60 percent of the hardwired connections, many disparate programmable devices, and several software programs were eliminated. New testing techniques were developed to test IEC 61850 communications, and wiring drawings were replaced with GOOSE messaging tables so that test technicians could identify the endpoints of the “virtual” wires.

The NGS implementation required completely new communication design methods, IED configuration, verification testing, and system commissioning. This article describes PPL’s process of developing best engineering practices for substation protection, integration, control, monitoring, metering, and testing. A discussion of these engineering practices and how they evolved provides valuable insight to engineers considering using one or more of the IEC 61850 protocols for peer-to-peer protection and automation or client/server methods for integration and automation.

Lessons learned were associated not only with new technology but also with new procedures, such as how test technicians selectively block signals that communicate over Ethernet without physically disconnecting the IED from the network. The paper also discusses PPL’s creation of a project team consisting of representatives from engineering, operations, standards, and relay testing to collectively resolve concerns associated with system testing, future expansion, and maintenance of this design.

I. INTRODUCTION

Previous PPL substation integration and automation systems utilized redundant programmable logic controllers (PLCs) as the substation data concentrator. Using discrete input/output (I/O) interface modules, interposing relays, and serial communications to IEDs via direct connection, substation information was collected by the “Substation” PLCs. The “Substation” PLCs would then pass this information to the SCADA RTU before the information was sent to the SCADA master.

Rather than propagate the existing PLC-based design, PPL engineers developed an alternative that incorporated the existing IEDs and improved the integration and automation, while also simplifying the system architecture. The new design relies on several protocols within IEC 61850 to support peer-to-peer relay communications, human-machine interface (HMI), and SCADA connections. Fully utilizing the available I/O in the relays and other IEDs essentially replaces large amounts of copper contact and transducer wiring with a few communications cables. The result eliminates equipment and reduces configuration, installation, commissioning, and maintenance costs.

However, this presents a new challenge. Although the new data acquisition methods promise to reduce the overall amount of labor, they also dramatically change the technology used for system configuration, installation, commissioning, and maintenance. These new technologies require new processes to provide an understanding of unseen data flow inside the communications network and a certainty that the protection and control systems will operate properly.

II. PREVIOUS COMMUNICATIONS DESIGN OVERVIEW

Prior to the new design, substations were designed with an integration architecture that included a combination of PLCs, direct-wired I/O modules, transducers, microprocessor-based relays, and other IEDs. A master “Substation” PLC passes remote controls issued from the SCADA master onto the “Bay” PLCs. The “Bay” PLCs pass on the SCADA commands to the protective relays, which, in turn, operate the substation apparatus. The “Bay” PLCs collect breaker status, alarms, and other digital inputs. Metering quantities were collected from separate transducers, and relay target statuses were collected directly from the multiple connected relays.

The “Substation” PLC concentrates the data from the “Bay” PLCs into a single database and passes data to the SCADA master using a single serial Modbus® protocol connection.

Because the PLC-centric design required extensive I/O wiring, interposing relays, additional protocol modules, and configuration expertise, PPL engineers initiated a program to investigate alternatives.

PPL eventually developed the following design criteria for their new substation IED network architecture:

- Eliminate the PLC, and reduce the number of programmable devices.
- Reduce I/O wiring.
- Utilize data within existing protective relays.
- Use communications wherever possible to collect

SCADA data.

- Apply protective relays to implement local automation.
- Implement new fiber-optic network communications systems for HMI, SCADA, and engineering access.
- Provide integrated network communications compatible with the existing online SCADA master.
- Ensure that the integration and automation system is compatible with the two different relay vendors.
- Eliminate the stand-alone sequential events recorder (SER) device and metering transducers.

III. BUSINESS CASE OVERVIEW

PPL found that they were able to achieve a number of subjective benefits by applying the new design. Specifically, the application of programmable "smart" digital relays and interoperable communications protocols provided the following benefits:

- Smart relays may be programmed to perform both control and protection functions, eliminating the need to install and maintain several devices.
- The use of industry-standard protocols, such as IEC 61850 and DNP, facilitates communication between relays and other manufacturers' devices and permits the application of the most cost-effective hardware.
- The same hardware design can be applied to various substation arrangements and voltage classes, reducing time for engineering and testing.
- The utility has the option of developing software and performing system integration either in house (to acquire and maintain expertise) or through contractors (when in-house engineering resources are committed to other projects).
- Panel space requirements are minimized because there are fewer "boxes" to mount on panels.
- Wiring from circuit breakers to panel terminals may be kept the same as the previous generation design.

Future designs can replace the wiring between the device and panel terminals with digital communications paths without impacting the new network IED design.

- From a physical viewpoint, relay replacement requires the rearrangement of only a small number of external wiring connections. Programming and settings changes may also be required.
- Substation engineers are generally more comfortable developing relay software than computer software because they are accustomed to working with relays.
- The NGS design is less complex than the prior PLC-based design.

These benefits directly impact the system's installation and life-cycle costs. Costs for the in-service station, using this new design, are not available for publication. However, a recent study compared system installation costs for the protection and control of a three-breaker, ring-bus switchyard based on the previous PLC-centric design and the new NGS relay network design. These results are summarized in Table I.

The installation cost for the first three-breaker, ring-bus-type substation design using the NGS design is greater than the cost of the previous PLC design. This is due to higher costs of the following:

- Training engineers, test technicians, and system operators.
- Developing standards, software, and test procedures.
- Documenting hardware and software.

Three-Breaker Ring Description	**Cost Difference Between First New NGS Design Installation and Previous PLC-Centric Standard**
Hardware	-$33,000
Software	+$70,200
Installation	-$33,000
Testing	-$11,000
Development	+$138,000
Training	+$36,000
Engineering	-$6,800
Drafting	-$11,5000
Documentation	+$60,000
Total Costs (First Installation)	**+$158,000**
Total Costs (Future Installations)	**-$144,000**

TABLE I
THREE-BREAKER, RING-BUS SWITCHYARD INSTALLATION COST COMPARISON

These increased costs are partially offset by savings in the following areas:

- Hardware costs are lower because many of the devices needed in the previous design are no longer required.

These functions are now performed in the relay.

- Installation and wiring costs are lower because there are fewer wire connections.
- Testing costs at the site are lower because there are fewer hardware devices and associated connections.
- Engineering and drafting costs are also reduced for the same reasons.

The cost of installing the new NGS design for subsequent projects is significantly lower than the cost of using the PLC-centric design. Engineering, drafting, software, and development costs are expected to be significantly lower than for the initial project, and most of the nonrecurring work is already complete.

IV. IMPLEMENTING NEW TECHNOLOGY WHILE MAINTAINING EXISTING WORK METHODS

A. HMI DEVELOPMENT

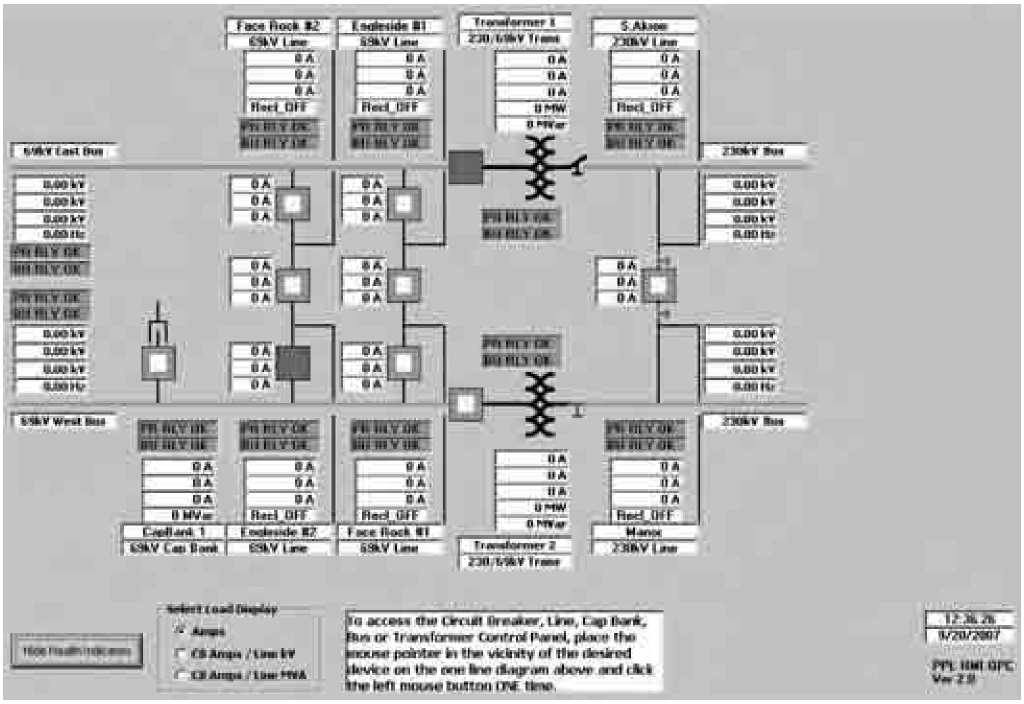
Existing standards within PPL utilize an in-house developed HMI system. The HMI interfaces with "Substation" PLCs via Modbus Plus to populate and animate the customized views. In order to ensure that the operators and engineers would adopt the existing HMI screens, a great amount of teamwork went into the process. This made it imperative that the new NGS HMI maintained the same look and feel as the previous PLC-based HMI, while manufacturing messaging service (MMS) became the data-update mechanism in the NGS. The new HMI development was planned so that it could be utilized at existing, new, or future substation designs, regardless of the protocols or mixture of protocols on the network.

In the end, PPL was successful in reusing much of the previous HMI development. A new HMI OPC (object linking and embedding for process control) interface was created so that existing HMI template views could be preserved and reused. Rather than associating the HMI value fields with a member of an incoming protocol map, OPC tags were used.

OPC is essentially the method by which protocol software and HMI software communicate to one another within the PC.

Any software that interfaces with OPC, such as Modbus, DNP, or IEC 61850 MMS protocol applications, can now update HMI tags. Now, this HMI design will support any of the protocols PPL chooses to use in the future. The OPC interface to the HMI supports the use of multiple protocols simultaneously as well.

The PPL HMI system was developed in house using Microsoft Visual Basic and tools from an OPC automation interface. The program was built around modular Microsoft ActiveX controls designed for each device. This provided PPL a great amount of flexibility to create customized applications for any substation configuration. The HMI one-line screen shows the device status, power system quantities, and reclosing preferences for the entire substation. Clicking on or near a device will load the control screen for that device, which displays a detailed view of the selected devices, along with their status and analog values. This screen also presents the user with controls for the selected device. At any point, the user can return to the one-line screen using on-screen navigation buttons. An example of an HMI one-line diagram screen capture is illustrated in Fig. 1.



To access the Circuit Breaker, Line, Cap Bank, Bus or Transformer Control Panel, place the mouse pointer in the vicinity of the desired device on the one line diagram above and click the left mouse button ONE time.

Fig. 1. Station HMI One-Line Diagram Screen Capture

B. COMMUNICATIONS COMMISSIONING AND CHECKOUT

As in the past, a sufficient methodical system checkout was performed during commissioning to verify proper data flow, and the results of the testing and verification were documented and archived for future review. PPL slightly modified their procedures to accommodate IEC 61850 MMS and GOOSE but continue to document and archive the results of communications checkout. These archives serve to provide future review of the test results and a starting point to perform additional testing. PPL found that when they added new functionality to an existing system, they needed only perform iterative partial testing. Using the thoroughly documented results of the previous system checkout, PPL engineers can confidently test new changes and only the parts of the network that the changes impact. Most importantly, because of their documentation procedures, PPL engineers know what needs to be tested as a result of these changes.

V. CHANGES TO METHODOLOGY

One major difference that affects all parts of commissioning and testing is that the new PPL NGS design uses a single Ethernet port on each IED. The second is that all PLCs are eliminated, and the upper-tier PLC is replaced with a communications processor.

A. USE MORE MICROPROCESSOR IED MULTIFUNCTION CAPABILITIES

Prior to the NGS design, the PPL design was mostly hardwired, with the exception of some PLC communications. The design incorporated three communications networks.

Redundant Modbus TCP networks for Bay PLC/Substation PLC communications and one Modbus Plus network for SCADA and metering communications were implemented.

Existing PLC-based designs were used as a starting point when embarking on the NGS design. Using functions already built into the microprocessor-based relay eliminated hardware and associated panel wiring. For example, the "Bay" PLC and fault detector were eliminated by moving breaker failure and direct transfer trip (DTT) logic functions into the relay. Digital transducers were also removed because the necessary data was already available in the microprocessor-based relays. Because the analog data were now available on the Ethernet port, PPL planned to use relay data to support the SCADA system, without the need for additional transducers. Previous substation designs used microprocessor-based relays for protection only. Other functions, such as fault detection, SER, etc., were performed by dedicated devices. The flexibility and reliability of microprocessor-based relays allowed the elimination of dedicated devices from the NGS design, because these functions now reside in the relay.

B. REPLACING WIRED TERMINATIONS WITH DIGITAL COMMUNICATIONS

Protective relays now perform many functions besides protection. The advantages that modern microprocessor-based relays provide over traditional relays are well documented.

These advantages include fault location, event reports, and programmable logic that allow many functions to be included in one device, thus saving hardware and wiring costs. One important complication of the technology shift is the increasing portion of the protection system design that resides in algorithms and logic in relays [1]. With the elimination of devices and hardwired connections, new methods of testing and documentation had to be developed. Previous substation designs utilized wiring diagrams or drawings for point verification. Points previously hardwired are now broadcast onto an Ethernet network via IEC 61850 GOOSE messages.

Table II provides a partial example of the peer-to-peer network communications design documentation. This information replaces point-to-point wire connections. It is used to facilitate testing and system troubleshooting.

C. COMMUNICATIONS MESSAGING ISOLATION FOR TEST

Challenges must be expected when a new design is developed. The NGS challenges were not always technical; some were procedural. For instance, how do test technicians selectively block signals communicating over Ethernet. To address these and other important issues, a project team consisting of representatives from engineering, operations, standards, and electrical testing was formed. Issues were discussed at length, and the system was designed to accommodate concerns associated with testing, scaling and expanding, and maintaining the design. For example, with previous substation designs, the need to block a particular function was imposed by opening a physical switch in the relay contact wiring circuit. The NGS utilizes a logic qualifier in the relay to block or enable GOOSE message broadcasts.

Because all IED communications are now interleaved through a single Ethernet port, PPL devised a way to isolate individual communications paths. When an operator chooses to block a GOOSE message, the contents are not actually updated. Although the IED GOOSE messages continue to be published, the payload, or data set, will not be updated with new values when the message is blocked. The HMI test display was modified to include a control to enable and disable the GOOSE data set update. When the operator chooses to disable GOOSE updates, a logic bit is set in the HMI and sent to the IED. The IED constantly checks this logic and its status with the update process. Using this method, individual bits or entire data set contents can be blocked from being updated in outgoing IED GOOSE publications.

D. COMMUNICATIONS MESSAGING CHANGES FOR HMI UPDATE

With the elimination of PLCs and single-function devices, the substation network had evolved. The Modbus Plus network was replaced by an Ethernet network, supporting multiple SCADA, peer-to-peer, and engineering access protocols. New software and programming tools were needed to configure the new system. Vendor-available software tools were used to develop relay logic, HMI programming, field simulation, testing, and documentation.

As stated before, the changes to the HMI were kept to a minimum. The previous HMI communicated to redundant PLCs to collect data. The NGS network now provides the HMI the ability to communicate with each relay. The HMI database update mechanism was changed from master/slave to client/server. This was done by simply changing the application that updated the HMI database from a SCADA protocol to IEC 61850 MMS. Using MMS, the database is now updated using client/server.

With the ability to communicate with each relay came the need for comparative logic in the HMI. When multiple relays provide data for one apparatus, such as a tie breaker, the HMI compares the data from all sources and flags any discrepancies.

The HMI provides the operator with the ability to view all data sources via a health-indicator button and determine which relay is not in agreement. This function is illustrated in Fig. 2. The operator also has the capability to remove the questionable IED from the scan.

Transmit Data Sets		Receive Data Sets				
		Primary Bay 1 Line 1 Relay				
Backup Bay 1 Line 1 Relay	1	1	2	3	4	5
	2	X				
Primary Bay 1 Line 2 Relay	1					
	2		X			
Backup Bay 1 Line 2 Relay	1					
	2			X		
Primary Bus Section 1 Relay	1					
	2				X	
Backup Bus Section 1 Relay	1					
	2					X

Bay Line Transmit Data Set 1	Bay Line Transmit Data Set 2
CB 1 Manual Trip/Close	Normal Bus Test Source
CB 1 Relay Trip	Alternate Bus Test Source
CB 2 Relay Trip	
CB 1 Auto Reclose Enable	
CB 2 Auto Reclose Enable	
CB 1 Out of Service	
CB 2 Out of Service	

TABLE II
PARTIAL EXAMPLE OF PEER-TO-PEER NETWORK COMMUNICATIONS DESIGN DOCUMENTATION

The health and status of the relays are constantly monitored within the HMI to ensure accurate data are presented to the user. Because the protection design includes redundant relaying, any data disruption from a primary relay will cause the HMI to shift to the backup device for any analog data.

Status data display is handled a bit differently. In order to ensure the relays remain consistent, the status of all the devices is combined using a Boolean AND statement. Any discrepancies between status values in the relays will be indicated with a yellow flag on the affected device(s). The HMI one-line and device control screens indicate abnormal health or status with a red or yellow alert icon for each affected relay. The HMI also allows the user the option to force any relay out of service and disregard any data coming from that device. This is useful when removing a relay from service to perform testing or maintenance without affecting the HMI status and analog quantities.

E. POINT VERIFICATION

PPL developed an HMI view that provides GOOSE monitoring to aid in verification of peer-to-peer digital communications interconnections. The application creates and displays GOOSE diagnostics as well as the data set contents from each IED. The application supports control of the GOOSE message behavior from the IEDs. Like the hardwire tests before, GOOSE test methods support iterative tests during commissioning as well as future changes and additions.

The test results are saved, and screen captures of the

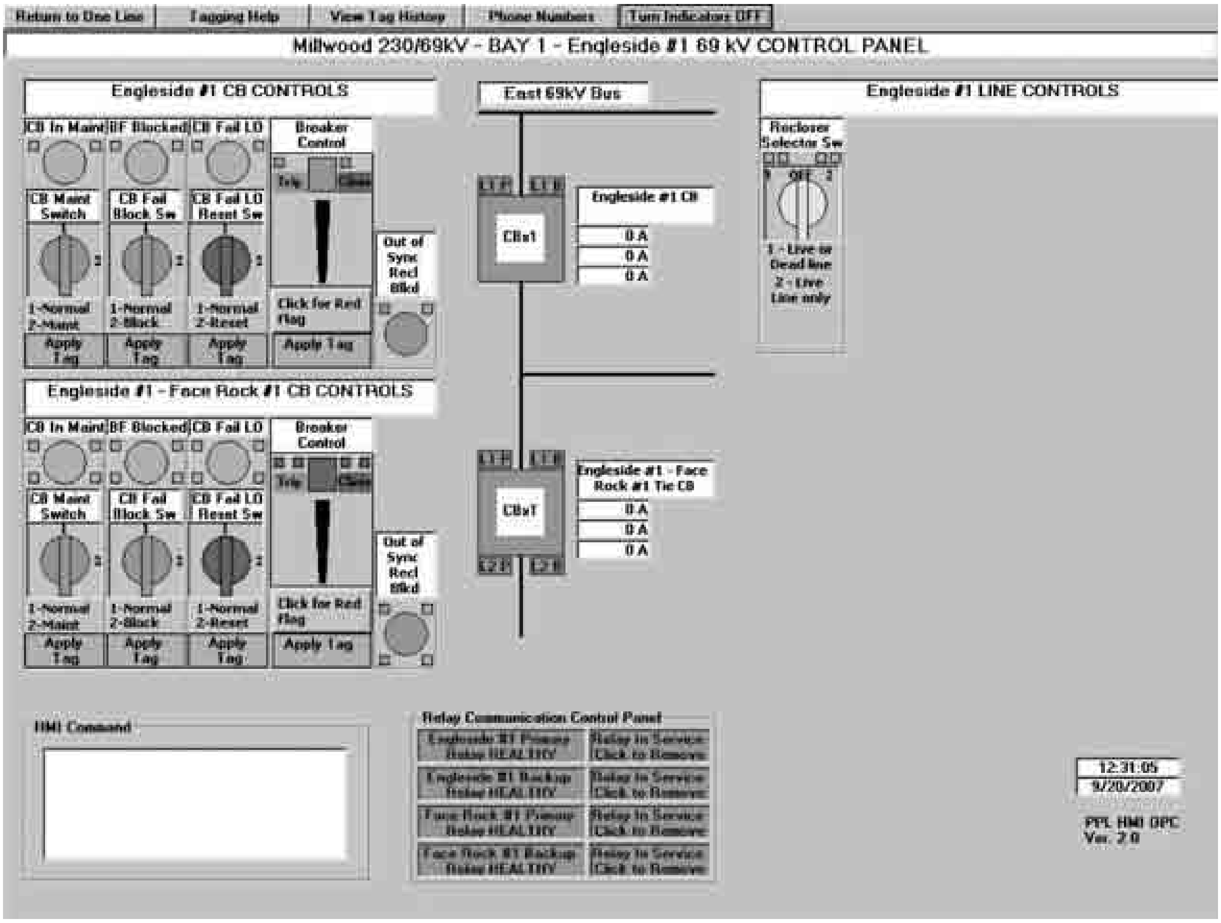


Fig. 2. HMI Display Illustrating Values From the IEDs and the IED Health

GOOSE monitor application are saved as test process artifacts. Fig. 3 illustrates an example screen capture of the GOOSE message tables used by technicians to identify "virtual connections" among IEDs.

The GOOSE system is designed around standard transmit data sets that serve two distinct purposes. The intent of the first transmit data set is to exchange protection data and ensure consistency between the redundant relaying data. Other transmit data sets serve the exchange of nonredundant relaying data or scheme data, such as bus differential tripping. A wired contact input on each relay permits blocking of all GOOSE data set transmissions by simply opening a test switch during relay testing or maintenance.

The GOOSE data set application IDs and the transmitting relay IP address easily identify the data source. All of the transmit data sets are multicast across the substation network.

Each relay is configured to subscribe to only the data sets it needs, and then the required data points are mapped into the relay logic.

The redundant relaying transmit data sets contain status data, such as maintenance switch status, breaker failure blocking switch status, line reclosing preference, bus test sources, and relay health. Protection data, such as breaker failure initiate, breaker failure lockouts, and transformer lockouts, were also included in this data set. The other transmit data sets contained data for bus differential tripping, breaker failure on a bus breaker, and bus testing after an operation.

GOOSE analog data are planned for use in future synchronism check and bus testing schemes but have not been implemented in current designs.

VI. NETWORKED IEDS IMPROVE SYSTEM CAPABILITIES

The act of integration realizes significant system benefits over traditional methods of measuring multiple field terminations, regardless of the protocol(s) or communications media used [2].

Systems constructed with integrated IEDs networked via wireless, copper, fiber, serial, or Ethernet connections combined into a local-area network (LAN) offer the following benefits:

1. Due to the reuse of data detected by a single IED and digitally communicated to integrated IEDs and other data clients, field terminations, associated wiring, labor, and maintenance are reduced.

2. By using IEDs that, in addition to their primary functions, also perform ongoing diagnostics of their own performance and that of the equipment they are monitoring, the quantity of unsupervised process and apparatus functions is reduced.

3. Confirming the availability and reliability of the method by which the data are being collected and alarming when the data path is broken, the minimized distance of the unsupervised data path between the field source and data client(s) greatly improves the value of the data.

Supervision is maximized by replacing traditional, unmonitored copper terminations with monitored digital communications at the IED closest to the field data. This, in turn, detects and alarms communications problems immediately.

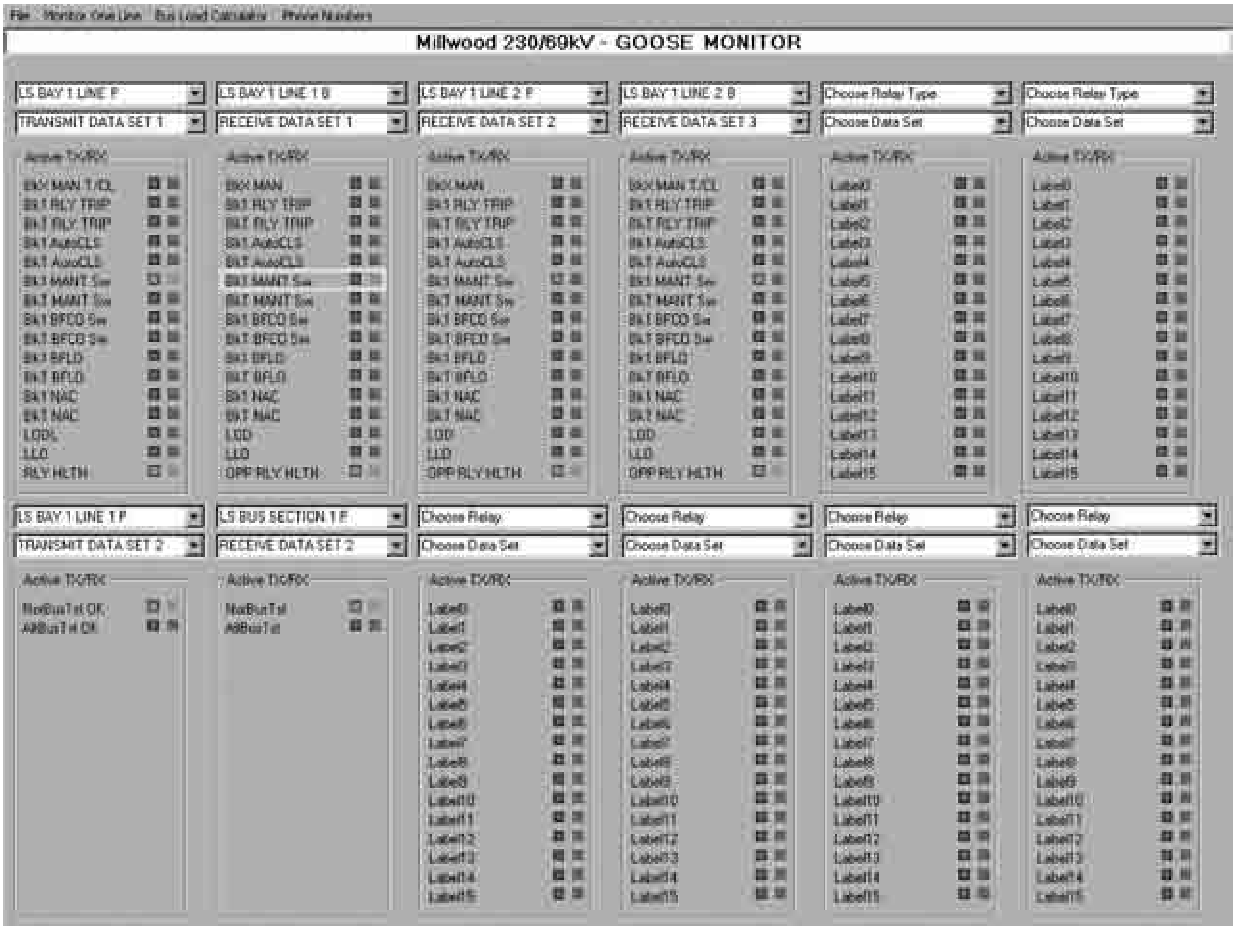


Fig. 3. GOOSE Message Table Example

4. Using methods that interleave multiple communications paths onto a single serial or Ethernet connection reduces the quantity of communications connections.

5. Because newer multifunction IEDs replace multiple, individual-purpose IEDs and because integration of IED data eliminates several traditional stand-alone systems, including those that perform SCADA, metering, SER, and digital fault recording, IED quantities are reduced.

6. Increased process and apparatus monitoring and control capabilities via the exchange and aggregation of data among many IED data sources rather than using a traditional implementation of only one IED and one data source per function. This ability to freely allocate data sources among IEDs networked using serial or Ethernet networks minimizes the importance regarding which IED is the data source and leads to more functional, flexible, and data-rich systems.

Any protocol standard used to network IEDs is capable of providing some of the benefits listed above. These protocols include DNP, Modbus, and IEC 60870. However, standards that include protocol suites to satisfy the aggregate of peer-to-peer, client/server, device configuration, and engineering access communications methods, such as the well-known relay vendor's interleaved protocols and IEC 61850, will provide the most benefit. These benefits are available whether the protocol suites are proprietary or nonproprietary; however, nonproprietary methods, in this case, led to better interoperability among the different vendor IEDs. Due to the application-specific requirements, however, it was necessary to support multiple methods of communications simultaneously to match different performance requirements. As an example, command line prompt via Telnet and file transfer via FTP are two different examples of standardized engineering access over Ethernet.

VII. ESSENTIAL IED-LEVEL TOOLS

Multifunction, microprocessor-based relays incorporate not only multiple relay functions in one "box" but also include programmable logic capabilities. These logic capabilities allow various "logic schemes" previously implemented by wiring auxiliary relays, timers, and devices together to be implemented in a single device using settings [3]. The technician and/or engineer tasked with testing or troubleshooting an installation can visualize the logical function as an electrical path on the diagram. However, verifying that messages and the data that they transfer are correctly moving over the Ether requires new, specialized tools.

A. GOOSE MESSAGE STATISTICS

In order to make GOOSE messages perform adequately, many traditional Ethernet mechanisms had to be removed and, in fact, a new and unique Ethertype had to be created. Each GOOSE message must fit within a single Ethernet frame, so each consecutive message has a unique sequence number incremented by one. The subscribing IED can determine if GOOSE messages are received out of sequence. Each time the message contents change, the message status number is incremented. This allows the subscribing IED to determine which message it has received and determine if the message payload has changed.

B. GOOSE MESSAGE QUALITY CALCULATION

There are several characteristics that need to be monitored to verify the correct publication and subscription of GOOSE messages. The receiving IED needs to verify both the quality of the messages as well as the quality of the data within the message. Communications diagnostics rely on message quality. Each IED should verify the message quality by combining the status of each of the following codes (Table II).

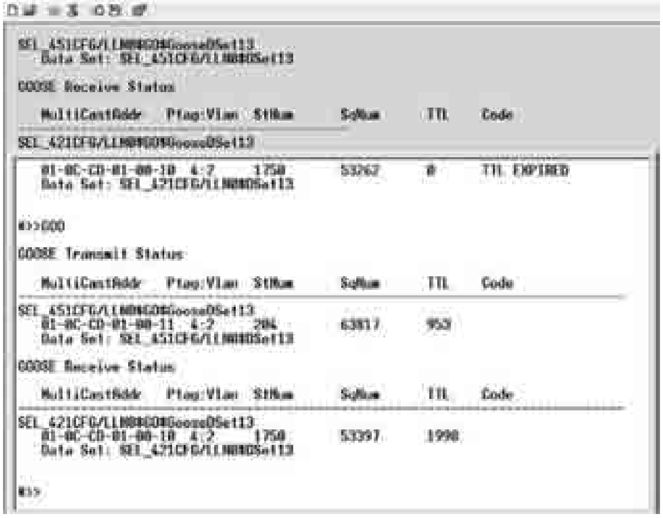
If any of these are set, the message quality indicates failure.

Message Statistics	Error Code
Configuration revision mismatch between publisher and subscriber	CONF REV MISMA
Publisher indicates that it needs commissioning	NEED COMMISSIO
Publisher is in test center	TEST MODE
Received message is decoding and reveals error	MSG CORRUPTED
Message received out of sequence	OUT OF SEQUENC
Message time to live expired	TTL EXPIRED

TABLE II
GOOSE MESSAGE ERROR CODES

C. GOOSE DIAGNOSTIC MESSAGE

Using the Telnet engineering access port, the GOOSE diagnostics are retrieved to show the configuration and status of incoming and outgoing GOOSE messages. The message shown in Fig. 4 displays the outgoing GOOSE message configuration and performance. Configuration information for each GOOSE message includes a message label, multicast address, priority tag, virtual LAN identifier, and data set name. Real-time statistics for each message include the status number, sequence number, time to live, and error code. If detected, an error code from Table II is displayed.



```
SEL_451CFG/LLN0$GO$GooseDSet13
   Data Set: SEL_451CFG/LLN0$DSet13

GOOSE Receive Status

   MultiCastAddr   Ptag:Vlan  StNum      SqNum      TTL     Code
SEL_421CFG/LLN0$GO$GooseDSet13
   01-0C-CD-01-00-10  4:2     1750       53267      0       TTL EXPIRED
   Data Set: SEL_421CFG/LLN0$DSet13

=>>GOO

GOOSE Transmit Status

   MultiCastAddr   Ptag:Vlan  StNum      SqNum      TTL     Code
SEL_451CFG/LLN0$GO$GooseDSet13
   01-0C-CD-01-00-11  4:2     204        63817      953
   Data Set: SEL_451CFG/LLN0$DSet13

GOOSE Receive Status

   MultiCastAddr   Ptag:Vlan  StNum      SqNum      TTL     Code
SEL_421CFG/LLN0$GO$GooseDSet13
   01-0C-CD-01-00-10  4:2     1750       53397      1998
   Data Set: SEL_421CFG/LLN0$DSet13

=>>
```

Fig. 4. GOOSE Diagnostic Statistics Retrieved via Telnet-Over-Ethernet LAN

D. GOOSE MESSAGE FAILURE ALARM AND NOTIFICATION

The subscribing IED calculates GOOSE message quality for each incoming GOOSE message. Because these methods are standardized, each IED is capable of calculating the GOOSE message quality for GOOSE messages from any vendor IED.

Once the IED has calculated the GOOSE message quality status, this value is available as a logic element within the IED. Each IED uses this status to block and enable logic, display GOOSE status on the IED front panel to aid troubleshooting, and alarm technicians via SCADA protocols or email, short message service (SMS), or telephone messages. The change of status state is also time-stamped and recorded as an SER.

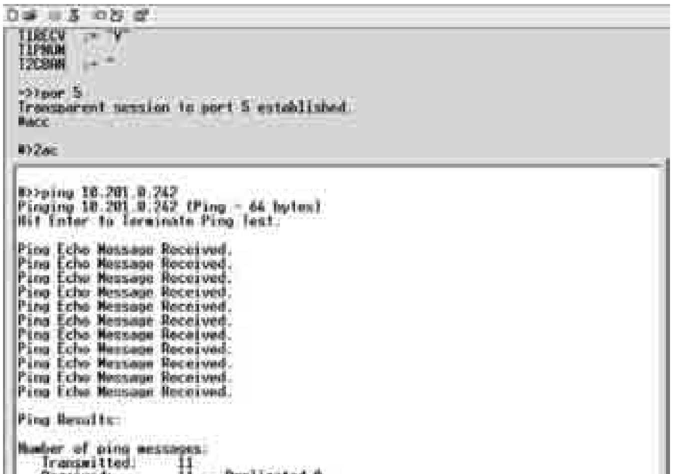
E. GOOSE MESSAGE RELIABILITY AND CHANNEL AVAILABILITY

Once recorded as a time-stamped SER, the GOOSE message quality status for each message is collected as a system-wide diagnostic. After commissioning, message quality will only fail when a message is corrupted or not received. The observation of failures will indicate the reliability of individual GOOSE messages. If the message quality failure is intermittent, the duration of the failures is calculated as the difference between timestamps. The aggregate of failure duration over a given amount of time determines the channel availability.

F. VERIFICATION OF PEER-TO-PEER VIRTUAL CHANNELS

Ethernet networks usually support multiple paths over the Ether between different points on the network. Routing and diagnostic methods support the verification of successful transmission between two points on the network, but not the path taken. The common standardized “ping” diagnostic executed by a client (e.g., an engineering workstation or SCADA/HMI computer) determines if it can contact the specified server over the network. The server in question, for example an IED, is identified by its network address. If successful, the ping application verifies that the client and server can make contact over the network. This implies that peer-to-peer applications using these two network addresses will also be successful. In order to verify connections to the entire network, the client pings all of the IEDs or other servers.

Although useful, this client/server ping verification back to a computer does not confirm that IEDs can contact each other over the network. Therefore, IEDs must ping each other to verify the peer-to-peer channel. Pinging between two IEDs is shown in Fig. 5, where the appropriate access level is protected by network security and IED passwords. In this example, a serial HyperTerminal session is used to interact with the IED



```
T1RECV   :-> V
T1PNUM
I2CBAN   :-> *

=>>por 5
Transparent session to port 5 established.
=acc

=>2ac

=>>ping 10.201.0.242
Pinging 10.201.0.242 (Ping - 64 bytes)
Hit Enter to Terminate Ping Test.

Ping Echo Message Received.
Ping Echo Message Received.
Ping Echo Message Received.
Ping Echo Message Received.
Ping Echo Message Received.
Ping Echo Message Received.
Ping Echo Message Received.
Ping Echo Message Received.
Ping Echo Message Received.
Ping Echo Message Received.
Ping Echo Message Received.

Ping Results:

Number of ping messages:
   Transmitted:     11
   Received:        11 -- Duplicated 0

=>>_
```

Fig. 5. HyperTerminal Display of One IED “Pinging” a Second Peer IED

Ethernet interface and cause it to ping the IED with address 10.201.0.242.

VIII. CONCLUSION

Using new IEC 61850 client/server methods to replace traditional master/slave methods was accomplished without making major changes to the previously designed HMI and SCADA interfaces.

PLCs were easily replaced with an IED network and communications processor by using more functionality available in the IEDs. Software tools were developed by PPL to accommodate new engineering and testing practices.

During the software design process, special considerations were made with regard to system expansion, troubleshooting, and maintenance of the system. It was important to PPL that the system was easy to expand, test, and maintain.

Messaging interoperability between peers depends on the device properties and the system architecture. Commissioning tests must be performed to verify that the communications behavior of a device as a system component is compatible with the overall network design. Stand-alone network test devices, HMI applications designed to observe network messaging, and internal IED diagnostics are all essential to configure, verify, and troubleshoot network communications.

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[3] Jason Young and Derrick Haas, "The Importance of Relay and Programmable Logic Documentation," presented at the 2008 DistribuTECH Conference and Exhibition, Tampa, FL, January 2008.

X. BIOGRAPHIES

Harold Fischer earned his BSEE from Lafayette College and is currently the relay test manager at PPL Electric Utilities Corporation. Since he joined PPL in 2000, he has been responsible for the design, installation, commissioning, and testing of protection, control, and substation communication equipment.

Jeffrey Gilbert received his BSEE degree from Lafayette College and his MSEE degree from Lehigh University. He has been employed in engineering positions by PPL Electric Utilities Corporation since 1972, where he currently is a senior staff engineer in substation engineering.

Greg Morton earned his BSEE degree from Rensselaer Polytechnic Institute. He joined PPL Electric Utilities Corporation in 2005, where he is currently a relay test support engineer. His experience includes the testing and maintenance of protection, control, and communications equipment.

David Dolezilek received his BSEE from Montana State University and is the technology director of Schweitzer Engineering Laboratories, Inc. He has experience in electric power protection, integration, automation, communications, control, SCADA, and EMS. He has authored numerous technical papers and continues to research innovative technology affecting our industry

Michael Boughman earned his BSEE from the University of North Carolina at Charlotte. He has over 20 years experience in substation integration and automation design and implementation. In 1999, he joined Schweitzer Engineering Laboratories, Inc. (SEL) as an integration application engineer.

RESISTANCE MEASUREMENTS THREE- AND FOUR-POINT METHOD

FOUR-POINT RESISTANCE MEASUREMENTS

Ohmmeter measurements are normally made with just a two-point measurement method. However, when measuring very low values of ohms, in the milli- or micro-ohm range, the two-point method is not satisfactory because test lead resistance becomes a significant factor.

A similar problem occurs when making ground mat resistance tests, because long lead lengths of up to 1000 feet are used. Here also, the lead resistance, due to long lead length, will affect the measurement results.

The four-point resistance measurement method eliminates lead resistance. Instruments based on the four-point measurement work on the following principle:

- Two current leads, C1 and C2, comprise a two-wire current source that circulates current through the resistance under test.
- Two potential leads, P1 and P2, provide a two-wire voltage measurement circuit that measures the voltage drop across the resistance under test.
- The instrument computes the value of resistance from the measured values of current and voltage.

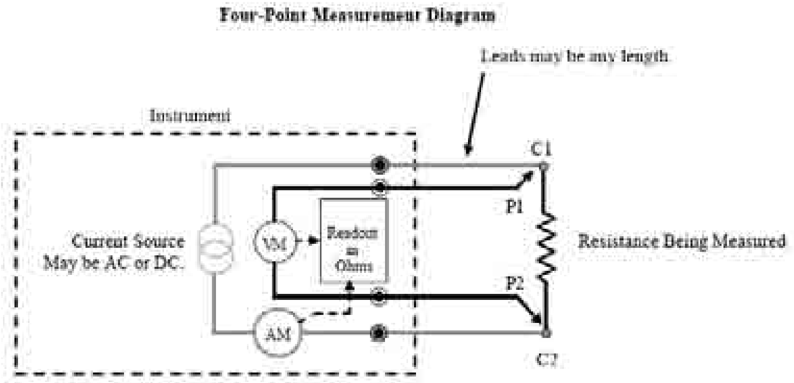


Figure 1

THREE-POINT RESISTANCE MEASUREMENTS

The three-point method, a variation of the four-point method, is usually used when making ground (earth) resistance measurements. With the three-point method, the C1 and P1 terminals are tied together at the instrument and connected with a short lead to the ground system being tested. This simplifies the test in that only three leads are required instead of four. Because this common lead is kept short, when compared to the length of the C2 and P2 leads, its effect is negligible. Some ground testers are only capable of the three-point method, so are equipped with only three test terminals. The three-point method for ground system testing is considered adequate by most individuals in the electrical industry and is employed on the TPI MFT5010 and the TPI ERT1500.

The four-point method is required to measure soil resistivity. This process requires a soil cup of specific dimensions into which a representative sample of earth is placed. This process is not often employed in testing electrical ground systems although it may be part of an initial engineering study.

PURPOSE/TPI INSTRUMENT FEATURES

PURPOSE

The purpose of electrical ground testing is to determine the effectiveness of the grounding medium with respect to true earth. Most electrical systems do not rely on the earth to carry load current (this is done by the system conductors) but the earth may provide the return path for fault currents, and for safety, all electrical equipment frames are connected to ground.

The resistivity of the earth is usually negligible because there is so much of it available to carry current. The limiting factor in electrical grounding systems is how well the grounding electrodes contact the earth, which is known as the soil/ground rod interface. This interface resistance component, along with the resistance of the grounding conductors and the connections, must be measured by the ground test.

In general, the lower the ground resistance, the safer the system is considered to be. There are different regulations which set forth the maximum allowable ground resistance, for example: the National Electrical Code specifies 25 ohms or less; MSHA is more stringent, requiring the ground to be 4 ohms or better; electric utilities construct their ground systems so that the resistance at a large station will be no more than a few tenths of one ohm.

TPI GROUND TEST INSTRUMENT CHARACTERISTICS

- To avoid errors due to galvanic currents in the earth, TPI ground test instruments use an AC current source.
- A frequency other than 60 hertz is used to eliminate the possibility of interference with stray 60 hertz currents flowing through the earth.
- The three-point measurement technique is utilized to eliminate the effect of lead length.
- The test procedure, known as the *Fall-of-Potential Method*, is described on the following page.

Test Products International
Three-Point Fall-of-Potential Ground (Earth) Resistance Testers
TPI MFT5010 Multi-Function Tester
Uses 570 Hz signal at less than 50 Volts RMS for Ground (Earth) Testing
TPI ERT1500 Earth Resistance Tester
Uses 800 Hz signal at less than 50 Volts RMS for Ground (Earth) Testing

Figure 2

THREE-POINT FALL-OF-POTENTIAL TEST PROCEDURE

GROUND TEST PROCEDURE

In the Fall-of-Potential Method, two small ground rods – often referred to as ground spikes or probes – about 12" long are utilized. These probes are pushed or driven into the earth far enough to make good contact with the earth (8" – 10" is usually adequate). One of these probes, referred to as the remote current probe, is used to inject the test current into the earth and is placed some distance (often 100') away from the grounding medium being tested . The second probe, known as the potential probe, is inserted at intervals within the current path and measures the voltage drop produced by the test current flowing through the resistance of the earth.

In the example shown on the following page, the remote current probe C2 is located at a distance of 100 feet from the ground system being tested. The P2 potential probe is taken out toward the remote current probe C2 and driven into the earth at ten-foot increments.

Based on empirical data (data determined by experiment and observation rather than being scientifically derived), the ohmic value measured at 62% of the distance from the ground-under-test to the remote current probe, is taken as the system ground resistance.

The remote current probe must be placed out of the influence of the field of the ground system under test. With all but the largest ground systems, a spacing of 100 feet between the ground-under-test and the remote current electrode is adequate. When adequate spacing between electrodes exists, a plateau will be developed on the test graph. Note: A remote current probe distance of less than 100 feet may be adequate on small ground systems.

When making a test where sufficient spacing exists, the instrument will read zero or very near zero when the P2 potential probe is placed near the ground-under-test. As the electrode is moved out toward the remote electrode, a plateau will be reached where a number of readings is approximately the same value (the actual ground resistance is that which is measured at 62% of the distance between the ground mat being tested and the remote current electrode). Finally, as the potential probe approaches the remote current electrode, the resistance reading will rise dramatically.

It is not absolutely necessary to make a number of measurements as described above and to construct a graph of the readings. However, we recommend this as it provides valuable data for future reference and, once you are setup, it takes only a few minutes to take a series of readings.

The electrical fields associated with the ground grid and the remote electrodes are illustrated on AN0009-5. An actual ground test is detailed on AN0009-6, and a sample Ground Test Form is provided on AN0009-7. See AN0009-8 for a simple shop-built wire reel assembly for testing large ground systems.

SHORT-CUT METHOD

The short cut method described here determines the ground resistance value and verifies sufficient electrode spacing – and it does save time. This procedure uses the 65' leads supplied with the TPI instruments.

- Connect the T1 instrument jack with the 15' green lead to the ground system being tested.
- Connect the T3 instrument jack with the red lead to the remote current electrode (spike) placed at distance of 65' (full length of conductor) from the ground grid being tested.
- Connect the T2 instrument jack with the black lead to the potential probe placed at 40 feet (62% of the 65' distance) from the ground grid being tested and measure the ground resistance.
- Move the P2 potential probe 6' (10% of the total distance) to either side of the 40' point and take readings at each of these points. If the readings at these two points are essentially the same as that taken at the 40' point, a measurement plateau exists and the 40' reading is valid. A substantial variation between readings indicates insufficient spacing.

THREE-POINT FALL-OF-POTENTIAL METHOD

INSTRUMENT SET-UP

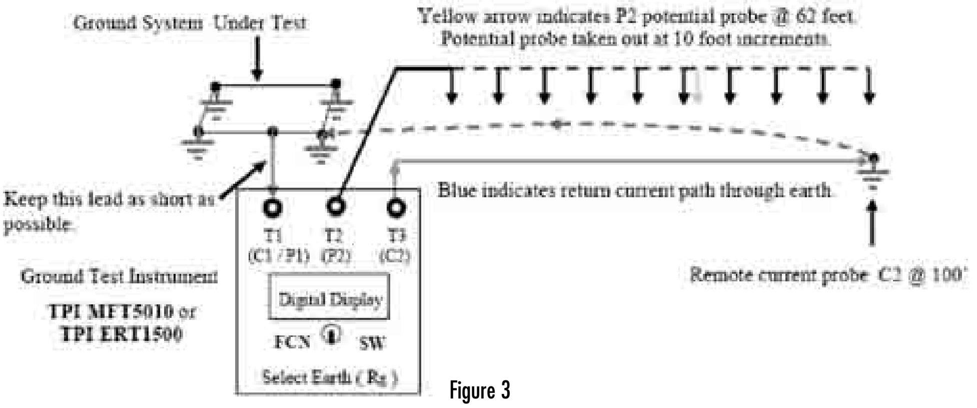

Ground System Under Test
Yellow arrow indicates P2 potential probe @ 62 feet.
Potential probe taken out at 10 foot increments.
Keep this lead as short as possible.
Blue indicates return current path through earth.
T1 (C1 / P1)
T2 (P2)
T3 (C2)
Ground Test Instrument
TPI MFT5010 or TPI ERT1500
Digital Display
FCN
SW
Select Earth (Rg)
Remote current probe C2 @ 100'

Figure 3

A NOTE ON INSTRUMENT LABELING CONVENTIONS

The TPI MFT5010 and TPI ERT1500 use the terminal designations T1 (C1/P1), T2 (P2), and T3 (C2).

The corresponding lead designations on the MFT5010 are E (Earth), S & H.

The corresponding lead designations on the ERT1500 are E (Earth), P (Potential), C (Current).

TEST CURRENT PATH

- Test Current (AC) flows from instrument T3 to remote current probe C2 on the red lead.
- Test Current flows from remote current probe C2 back through the earth to the ground being tested as shown by dashed blue line.
- Test current flows out of ground grid back to instrument T1 on the short green lead.
- Black potential lead P1 is connected to instrument T2 and is taken out at 10' increments. It measures voltage drop produced by the test current flowing through the earth. (P1 to P2 potential)

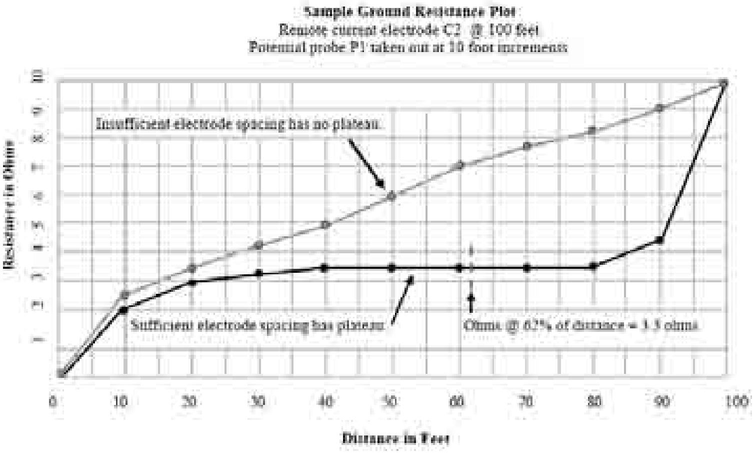


Figure 4

EQUAL-POTENTIAL PLANES

THE EXISTENCE OF EQUAL-POTENTIAL PLANES

- When current flows through the earth from a remote test electrode (in the case of a ground test) or remote fault, the voltage drop which results from the flow of current through the resistance of the earth can be illustrated by equal-potential planes. The equal-potential planes are represented in the dashed lines in the drawings below where the spacing between concentric lines represents some fixed value of voltage.
- The concentration of the voltage surrounding a grounding element is greatest immediately adjacent to that ground. This is shown by the close proximity of lines at the point where the current enters the earth and again at the point where the current leaves the earth and returns to the station ground mat.
- In order to achieve a proper test using the Fall-of-Potential Ground Test Method, sufficient spacing must exist between the station ground mat being tested and the remote current electrode such that the equal-potential lines do not overlap. As shown by the black line in the Sample Plot, adequate electrode spacing will result in the occurrence of a plateau on the resistance plot. This plateau must exist at 62% of the distance between the ground mat and the remote electrode for the test to be valid. Insufficient spacing results in an overlap of these equal-potential planes, as illustrated at the bottom of this page and by the red line on the Sample Plot.
- See the Safety Note on AN0009-6 for information on the hazards of Step and Touch-Potentials.

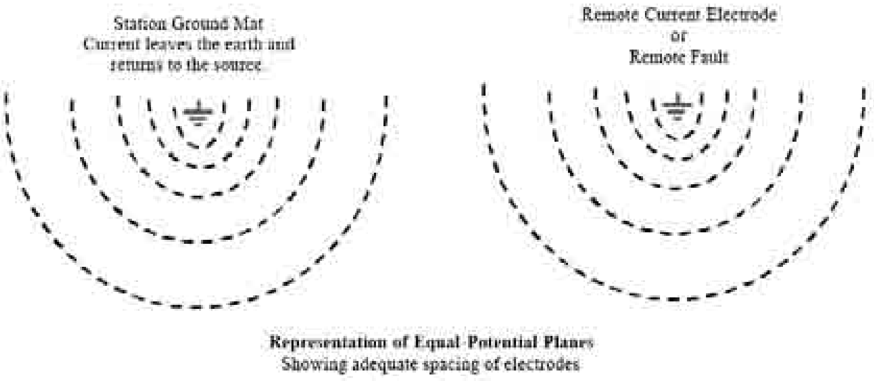
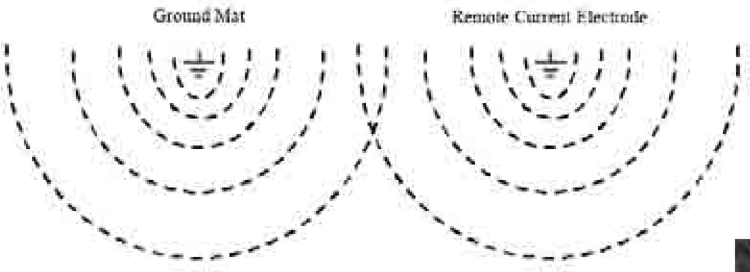

Station Ground Mat
Current leaves the earth and
returns to the source
Remote Current Electrode
or
Remote Fault
Representation of Equal-Potential Planes
Showing adequate spacing of electrodes

Figure 5



Representation of Equal-Potential Planes
Showing inadequate spacing between the established ground and remote test electrode

Figure 6

ACTUAL FIELD TEST

This actual ground test was conducted on a pad-mount transformer in a rural mountain area. The single-phase transformer is supplied by a 12470/7200 volt grounded wye primary and the transformer is grounded by its own ground rod as well as being tied to the system neutral which is grounded at multiple points along the line. The distribution line is overhead with just the "dip" to the transformer being underground.

Setting-Up the Ground Tester

TPI MFT5010 Instrument
Showing the 50 foot reading of 4.0 Ohms.

Ground Test Data
Remote Current Probe C2 @ 100 Feet

P2 Distance from Transformer in Feet	Instrument Reading in Ohms
10	1.83
20	3.59
30	3.85
40	3.95
50	4.0
60	4.25
62*	4.3
70	4.5
80	5.4
90	7.3
100	25.02

* Actual Ground resistance.

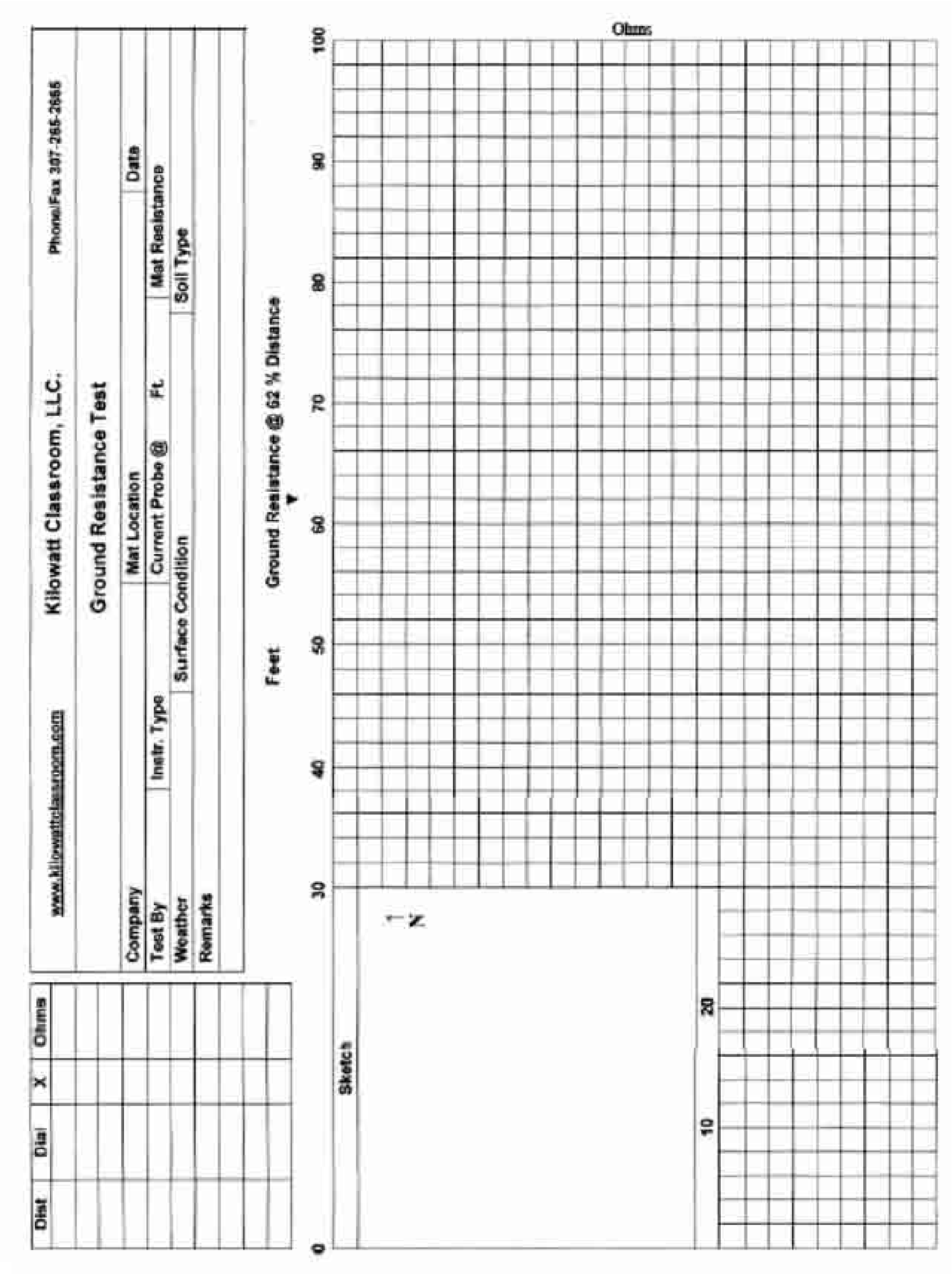
TEST PROCEDURE

Terminal T1 of the TPI MFT5010 tester was connected to the transformer case ground with the short green lead. The remote Current Probe C2 was driven in the ground at a location 100 feet from the transformer and connected to Terminal T3 of the instrument with the red test lead.

Terminal T2 of the tester was connected, using the 100' black lead, to the P2 potential probe. This ground stake was inserted into the ground at 10' intervals and a resistance measurement was made at each location and recorded in the table above.

The relatively constant readings in the 4 ohm range between 40 and 70 feet are a definite plateau that indicates sufficient lead spacing. The initial readings close to the transformer are lower, and there is a pronounced “tip-up” as the P2 probe approaches the remote current electrode C2.

The measured ground resistance at 62 feet (62% of the distance) was 4.3 ohms and is taken as the system ground resistance. This is an excellent value for this type of an installation.



www.kilowattclassroom.com

Kilowatt Classroom, LLC.

Phone/Fax 307-265-2665

Ground Resistance Test

Company Mat Location Date

Test By Instr. Type Current Probe @ Ft. Mat Resistance

Weather Surface Condition Soil Type

Remarks

Dist	Dist	X	Ohms

Feet Ground Resistance @ 62 % Distance

Ohms
0
10
20
30
40
50
60
70
80
90
100
Sketch
N

SAFETY NOTE – POSSIBLE EXISTENCE OF HAZARDOUS STEP AND TOUCH POTENTIALS

It is recommended that rubber gloves be worn when driving the ground rods and connecting the instrument leads.

The possibility of a system fault occurring at the time the ground test is being conducted is extremely remote.

However, such a fault could result in enough current flow through the earth to cause a possible hazardous step potential between a probe and where the electrician is standing, or hazardous touch potential between the probes and the system ground. The larger the system, in terms of available fault current, the greater the possible risk.

REEL ASSEMBLY

A SHOP-BUILT GROUND TEST WIRE REEL ASSEMBLY

This simple, low-cost, and easy-to-build wire reel assembly is handy for making Ground (Earth) Resistance measurements on large ground systems. The unit shown below has 500 feet of wire for testing medium-to-large ground fields typical of those found in industrial plants and substations. For testing even larger systems, such as those installed for power generating plants, wire lengths of 1000 feet can be used. Wrap-on wire markers are installed every ten feet on the current lead to simplify placement of the remote current and potential probes. Your electrical distributor will probably have empty surplus reels available for the asking – the ones shown below are about 12 inches in diameter. The conductor is standard #12 THHN. Even though the TPI ERT1500 and the MFT5010 use an AC test signal, the test results are unaffected by the inductance of any wire left on the reels.

THE ART OF MEASURING LOW RESISTANCE

Tee Sheffer and Paul Lantz, Signametrics

Don't heap all the blame for a wrong measurement on the DMM (Delayed Neutron Monitor). There can be several less obvious sources of the errors.

Testing assemblies and components usually includes checking the continuity of connectors, wires, traces, and low-value resistive elements. Such applications typically require both a DMM and a switching system.

Many users select a DMM and switching cards based only on the specifications of the DMM and later are surprised to find that their measurements are an order of magnitude less accurate than expected. Many users don't recognize the error as a system problem and conclude that the DMM is not meeting its specification.

Making accurate, stable, and repeatable resistance measurements is an art. There is plenty of technology involved, but the art is an important part, especially when you are measuring low resistance values.

To achieve your accuracy goal, you need to understand the error sources in your application. It is important to start with a good DMM. But, there are significant error sources outside the DMM, some of which may not be obvious. Things may be more complex than they seem, and some types of errors may be misinterpreted.

LIMITATIONS AND ERROR SOURCES

Not all materials are created equal. Most connectors and test probes are made of beryllium-copper or phosphor-bronze materials that closely match the electromotive force (EMF) of copper. For this reason, they do not cause significant thermally induced voltage errors.

However, relays and some other devices use nickel-iron alloys that do not match the properties of copper. These can cause significant thermal EMF errors. Thermal voltages are generated when there is a mismatch of materials combined with a temperature difference.

This is the same principle that makes thermocouples work as temperature sensors. If you expect readings that are accurate within a few milliohms, this is a big issue. This error source also affects higher value resistance measurements, but to a lesser degree.

It is easy to overlook second-order specifications of a DMM, such as current drive levels used for resistance measurement. These specs may be in small print or missing, but they are important. For measuring low resistance, this spec tells what you can expect from the DMM. The accuracy specs of the DMM don't tell the whole story. For example, the Signametrics SMX2064 PXI DMM uses a 10-mA current source, while most other DMMs are limited to 1 mA or less. Remember Ohm's Law: V = I x R means that 10 times the current produces 10 times the voltage being sensed across the resistor. This larger signal is less susceptible to external errors and noise and provides more signal to measure.

The larger signal almost always produces a more accurate measurement. It is confusing to compare two DMMs having similar specifications in ohms if one has 10 times the current drive. The two are not the same. The one with the higher current will perform better, especially in a system.

Good DMMs can measure signals down to a few microvolts. If you need to measure a resistance down to a few milliohms, a 1-mA test current only produces 1 µV of signal per 1 mΩ of resistance. In other words, you are operating right at the resolution limit of the DMM.

With a 10-mA test current, there are 10 µV of signal per 1 mΩ of resistance. As a result, a DMM that uses 10x as much current for this test will give about 10x improvement in accuracy, stability, and repeatability for very low values.

If your test has serious throughput requirements and you need to make hundreds of measurements per second, having a stronger signal combined with good noise performance in the DMM makes a huge difference. Remember that the DMM's accuracy at higher speeds may be much more important than its best accuracy.

TWO-WIRE

Everyone knows how easy it is to measure resistance using a two-wire connection. However, for low resistance, a two-wire connection has disadvantages (Figure 1).

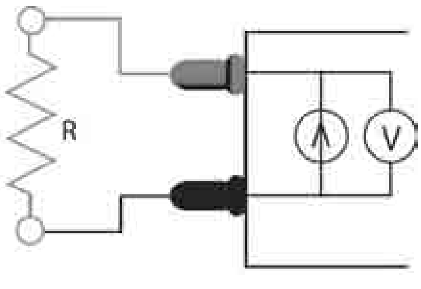


Figure 1. Two-Wire

Test leads frequently add >1 Ω of resistance, and your test probe may add another 0.1 Ω of contact resistance to the measurement. These errors are significant if you are measuring 20 Ω.

You can eliminate most of the test-lead errors from a two-wire connection by shorting the leads and setting the Relative-Ohms control. This enables the DMM to subtract the test-lead resistance from the readings that follow. This is a very handy tool when you are doing manual testing, but it is less useful in an automated test.

FOUR-WIRE

A four-wire connection is the standard method for measuring low resistance. It eliminates the resistance of the test leads from the measurement. One pair of leads carries the test current while the other pair of leads senses the voltage across the resistor under test (Figure 2).

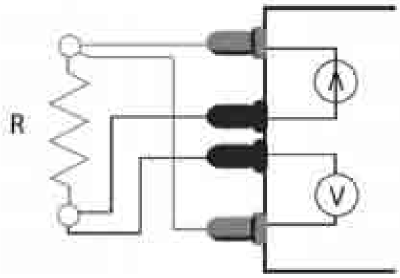


Figure 2. Four-Wire

The resistance of the current-carrying leads doesn't matter because they are not in the measurement path. The resistance of the sensing leads doesn't matter since they don't carry any current.

A four-wire connection is not immune to thermal EMF errors caused by mismatched materials. This usually is not important in manual testing situations, but it is a major issue in automated systems where a relay switch is used.

SIX-WIRE

What if the resistor you want to measure is in a circuit with other components or resistors as in networks or on a loaded circuit board? Then you need a six-wire guarded connection. This method makes it possible to measure resistance in situations where it would be impossible otherwise. The SMX2064 DMM offers this capability (Figure 3).

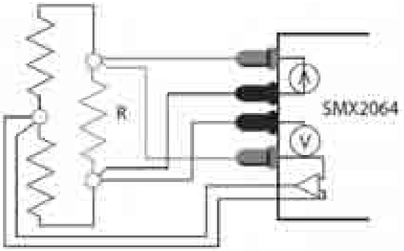


Figure 3. Six-Wire Guarded In-Circuit Measurement

A guard amplifier drives the junction of parallel components to a voltage level that prevents any of the test current from leaking away from the resistor under test. This is a standard method used by large ATE in-circuit test systems. With the right DMM, you can implement it too.

MEASURING THROUGH A SWITCH MATRIX

Many applications are for production test. In these cases, it is almost always necessary to perform multiple tests and measure multiple points. You usually do this by putting a switching card or a matrix ahead of the DMM. It is important to note that the switching card can be a major source of error, particularly when measuring low resistance.

TWO-WIRE WITH A SWITCHING CARD

How does adding a switching card affect your two-wire resistance measurements? Two-wire resistance measurements certainly are attractive because you can fit twice as many two-wire measurements onto a card as you can four-wire measurements.

The economics are attractive. Perhaps you can put a short circuit on one of the inputs to the switching card and measure that short to make a Relative-Ohms measurement? This line of reasoning also might lead you to select the highest density switching card possible.

However, there are reasons to be careful. A typical switching card does not have the same resistance through all of its channels. Channel 0 may add 0.2 Ω to the reading while Channel 20 may add 0.8 Ω. Consequently, measuring a short on one does not give a good compensation for the other because they do not have the same resistance.

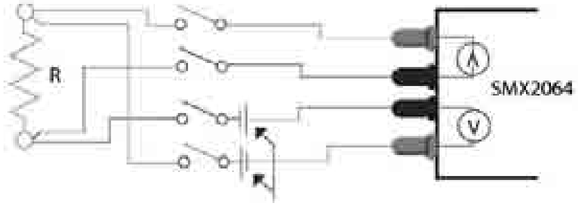
Even if you could correct for the difference in channel-to-channel resistance, relays typically have about 50 mΩ of contact resistance that will shift around by 20 mΩ from one reading to the next. You might think that high-current relays will have lower contact resistance, but it doesn't work that way. High-current relays usually have silver-plated contacts that give low resistance for currents above 100 mA. Unfortunately, silver-plated contacts have a high and unpredictable contact resistance for currents less than 50 mA.

Relays are made of nickel-iron materials, and they all have problems with thermal EMFs. Frequently, this error source is not specified for high-density switching cards. If not, the thermal voltages probably are around 100 µV. If your DMM uses 10 mA to make this measurement, the switching card adds 10 mΩ of error to the measurement. If your DMM uses only 1 mA, the switch will add 100 mΩ of error to the measurement.

Keep in mind that this error voltage is made up of all of the closed relay contacts connected to the sense lines of the DMM. The more complex the switching system is, the higher the error will be.

FOUR-WIRE WITH A SWITCHING CARD

Using a four-wire connection through your switching card takes care of the resistance issues associated with the switching card. This accuracy improvement happens at the expense of reduced channel density. However, it does not take care of the thermal EMF problems that come with some switching cards (Figure 4).



THERMAL VOLTAGE ERRORS, NOT CORRECTED

Figure 4. Four-Wire Switching Card

One way to reduce this error is to use a DMM with the Offset-Ohms function. However, this method is very slow, it adds noise, and it is limited in its capability to reduce the error. For best results, start with a high-quality switching card that is specified for low thermal EMF error.

How big a problem are thermal EMF voltages in relay switches? A high-quality switching card has about 10 µV while a typical one has >100 µV of thermal voltages. There are a few instrumentation quality switches that exhibit 1µV or less.

Take a look at Figure 5 to see the effect. The plots depict the specs of two similar DMMs. One of the DMMs uses 1-mA excitation current while the other uses 10 mA. There are some things to note:

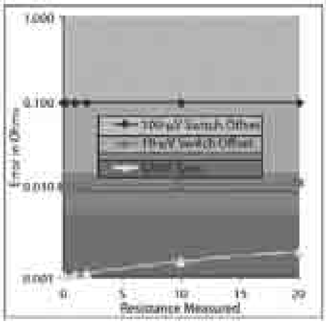


Figure 5a. 1-mA Ohms Excitation

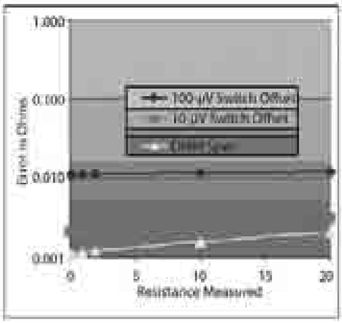


Figure 5b. 10-mA Ohms Excitation

- Both DMMs have very similar specifications.
- As soon as you combine them with a relay card that has 10-µV offset, the system error is considerably greater than the DMM spec. For the DMM with 10-mA excitation, the system error is almost two times the DMM spec. For the DMM with 1-mA excitation, the system error is almost 10 times the DMM spec.
- If you combine the DMMs with a relay card that has 100-µV offset, the error becomes huge. For the DMM with10-mA excitation, the system error is almost 10 times the DMM spec. For the DMM with 1-mA excitation, the system error is almost 100 times the DMM spec.
- The effect of the relay offset voltages overwhelms the DMM specifications in both cases, but the DMM that uses 10-mA excitation current produces a system spec between five and 10 times better than the DMM that uses 1-mA excitation.

SIX-WIRE WITH A SWITCHING CARD

A six-wire resistance connection works just fine with a switching card as long as the card is organized to support it. Remember that a six-wire connection does not increase the accuracy of your measurement unless other resistors in the circuit need to be guarded. This is still the only way to guard-out parallel resistors that otherwise would make the measurement impossible.

EXAMPLES

A manufacturer of semiconductor protection devices uses an SMX2064 on its low-resistance four-wire range to accurately measure resistances around 20 Ω before and after hitting the device with a high test voltage. Because the SMX2064 can take an accurate measurement in as little as 1 ms, test throughput is high.

A manufacturer of hybrid circuits uses an SMX2064 to measure resistance values of less than 100 mΩ. In this case, speed is not an issue, but getting a useable measurement is. Other DMMs that use only 1-mA excitation current did not qualify to do the job.

CONCLUSION

If you need to measure low resistance values, you benefit by using a DMM that has a 10-mA excitation current. A 1-mA source gives a much weaker signal to measure and presents system-level problems, particularly if there are switching cards involved. If you expect a stable, accurate result, you almost certainly need to use a four-wire connection.

The accuracy spec of the DMM is important but not the whole story. Remember that everything in the measurement path affects the accuracy of the measurement, especially switching cards. Your best bet is to combine a DMM with good ohms specifications and high test current and a switching card with a low thermal EMF spec, preferably an instrumentation type.

WHAT IS HIPOT TESTING?

Cirris Systems Corp.

Many people are familiar with a continuity test. A continuity test checks for “good connections”. You do a continuity test by seeing if current will flow from one point to another point. If current flows easily enough, then the points are connected. Many people aren’t familiar with a hipot test. “Hipot” is short for high potential (high voltage). A hipot test checks for “good isolation”. You do a hipot test by making sure no current will flow from one point to another point. In some ways, a hipot test is the opposite of a continuity test.

Continuity Test: “Make sure current flows easily from one point to another point.”

Hipot Test: “Make sure current won’t flow from one point to another point (and turn up the voltage really high just to make sure no current will flow).”

In the simple case, a hipot test takes two conductors that should be isolated and applies a very high voltage between the conductors. The current that flows is watched carefully. Ideally, not much current will flow. If too much current flows, the points are not well isolated and they should fail the test.

WHY HIGH VOLTAGE TEST?

You use a hipot test to make sure you have good isolation between the parts of a circuit. Having good isolation helps to guarantee the safety and quality of electrical circuits. Hipot tests are helpful in finding nicked or crushed insulation, stray wire strands or braided shielding, conductive or corrosive contaminants around the conductors, terminal spacing problems, and tolerance errors in IDC cables. All of these conditions might cause a device to fail.

WHAT KINDS OF HIGH-VOLTAGE TESTS ARE THERE?

There are three common high voltage tests.

- Dielectric Breakdown Test
- Dielectric Withstanding Test
- Insulation Resistance Test

WHAT IS “DIELECTRIC BREAKDOWN TESTING”?

With dielectric breakdown testing you are trying to answer the question “How much voltage can I apply between the wires before the insulation fails?” You increase the voltage until the current suddenly increases. You are finding the highest voltage the cable can stand before it fails. Once the cable fails it is usually damaged or destroyed.

WHAT IS “DIELECTRIC WITHSTAND TESTING” (DW)?

In dielectric withstand testing, you are trying to answer the question “Will this cable withstand a required voltage for a required time?” You apply the voltage for the amount of time and watch the current that flows. Ideally, no current flows and the cable is not harmed.

WHAT IS “INSULATION RESISTANCE TESTING” (IR)?

In insulation resistance testing, you are trying to answer the question “Is the resistance of the insulation high enough?” You apply a voltage and very carefully measure the current. You then calculate the insulation resistance using Ohm’s Law ($R = V/I$).

HOW DO THESE “HIPOT” TESTS AFFECT QUALITY?

All of these tests are tools you can use to better understand how a cable will perform and to monitor any changes in the cable’s performance.

Dielectric breakdown testing is used in product design and qualification stages. It helps establish the maximum voltage of the design. It can also be used on a random sample basis to verify that the maximum voltage is not changing. Dielectric breakdown testing may be required during the development of assemblies used in critical applications.

Many test specifications require a Dielectric Withstand Test on every cable produced. The test is usually done at about 75% of the typical breakdown voltage. It is done as a safety net. The test is sensitive to arcs or corona, so it often finds terminal spacing problems, over-mold problems, tolerance errors in IDC cables, or any problem that might produce arcs. This test doesn’t significantly degrade the cable.

The Insulation Resistance test is typically done on every cable tested. It is usually done at 300 to 500 VDC with 100 to 500 Megahoms resistance. The test is very sensitive to contamination in the assembly process. Solder flux, oils, mold release agents, and skin oil all can cause problems. This test excels at identifying insulation that will conduct in the presence of moisture. Doing this test on every cable allows you to detect contamination changes in the manufacturing process.

WITH ALL THE HIGH VOLTAGE BEING USED, WHAT ABOUT MY SAFETY?

During a hipot test, you may be at some risk. The risk can be reduced by using a tester designed to be safe and by using that tester according the manufacturer’s instructions.

Products being designed today usually must comply with product safety regulations. Some of these regulations work to reduce the chance of you receiving a harmful electrical shock. Modern equipment is more likely to follow these regulations. When it comes to hipot charge, energy, and voltage, you should select the “safest” machine that will still test your cables.

To minimize your risk of injury from electrical shock ,make sure your hipot equipment follows these guidelines:

- The total charge you can receive in a shock should not exceed 45 uC.
- The total hipot energy should not exceed 350 mJ.
- The total current should not exceed 5 mA peak (3.5 mA rms)

- The fault current should not stay on longer than 10 mS.
- If the tester doesn't meet these requirements, then make sure it has a safety interlock system that guarantees you cannot contact the cable while it is being hipot tested.

These guidelines come from the test standard EN61010-1, Safety requirements for electrical equipment for measurement, control and laboratory use, April 1993, CENELEC. Over the last decade, many of the safety regulations have been harmonized (standardized) and EN61010-1 is similar to UL 61010A-1 (formerly UL3101-1).

While you are testing cables, there are several things you can do to reduce the risk even more:

- Verify the correct operation of the safety circuits in the equipment every time you calibrate it.
- Follow all of the manufacturer's instructions and safety guidelines.
- Don't touch the cable during hipot testing.
- Allow the hipot testing to complete before removing the cable.
- Wear insulating gloves.
- If you have any health condition that can be aggravated by being startled then don't use the equipment.
- Don't allow children to use the equipment.
- If you have any electronic implants then don't use the equipment.

WHERE IS THE HIGH VOLTAGE APPLIED?

To understand a how hipot testing works, you'll need to understand where to connect the high-voltage supply. Hipot testers usually connect one side of the supply to safety ground (earth ground). The other side of the supply is connected to the conductor being hipoted. With the supply connected like this, there are two places a given conductor can be connected: high voltage or ground.

When you have more than two contacts to be hipot tested, you connect one contact to high voltage and connect all other contacts to ground. Testing a contact in this fashion makes sure it is isolated from all other contacts.

What happens when you test something more complicated than just contacts? A series of contacts that are connected with wires, resistors, capacitors, diodes, and other components is called a "network" of connections (or "net"). To hipot test a net, you connect all of the contacts in the net to high voltage and connect all other contacts in the device to ground. For example, if you have a wire that connects two pins, the high voltage will be simultaneously applied to both of those pins and the entire wire will be raised in voltage. All other wires and pins will be held at ground. If you have a resistor that connects two pins, both pins are raised in voltage, the voltage drop across the resistor is always zero. The entire resistor is raised in voltage. In short, all pins of a component see the same voltage at all times. Applying the voltage in this fashion makes sure the body of the component is isolated from the rest of the device.

WHERE IS THE CURRENT MEASURED?

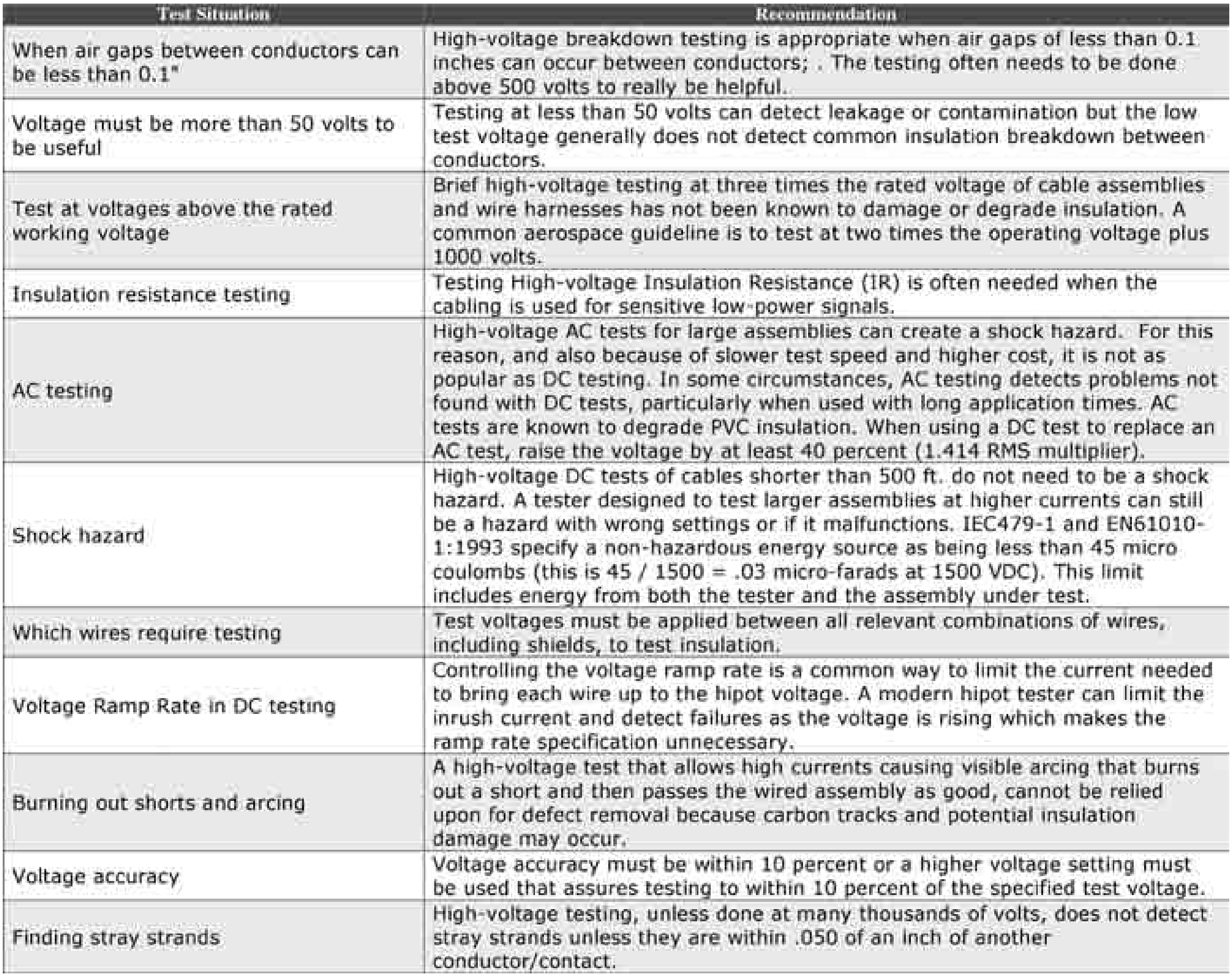
During the hipot test, the current that flows out of the high voltage supply is measured.

WHAT CAUSES CURRENT TO FLOW THROUGH AN INSULATOR?

Insulation "does not conduct". But if you use enough voltage, even the best of insulations will allow some current to flow. You may wonder why the current flows? There are several reasons current will flow through insulation during a hipot test. Resistance, capacitance, arcs, electrochemical effects, and corona are all effects that describe current flow. All of these effects add together during a hipot test to shape the outcome of the test.

USING VOLTAGE TO DETECT INSULATION DEFECTS

Here are some guidelines for using voltage to find insulation problems(chart on next page).



Test Situation	Recommendation
When air gaps between conductors can be less than 0.1"	High-voltage breakdown testing is appropriate when air gaps of less than 0.1 inches can occur between conductors; . The testing often needs to be done above 500 volts to really be helpful.
Voltage must be more than 50 volts to be useful	Testing at less than 50 volts can detect leakage or contamination but the low test voltage generally does not detect common insulation breakdown between conductors.
Test at voltages above the rated working voltage	Brief high-voltage testing at three times the rated voltage of cable assemblies and wire harnesses has not been known to damage or degrade insulation. A common aerospace guideline is to test at two times the operating voltage plus 1000 volts.
Insulation resistance testing	Testing High-voltage Insulation Resistance (IR) is often needed when the cabling is used for sensitive low-power signals.
AC testing	High-voltage AC tests for large assemblies can create a shock hazard. For this reason, and also because of slower test speed and higher cost, it is not as popular as DC testing. In some circumstances, AC testing detects problems not found with DC tests, particularly when used with long application times. AC tests are known to degrade PVC insulation. When using a DC test to replace an AC test, raise the voltage by at least 40 percent (1.414 RMS multiplier).
Shock hazard	High-voltage DC tests of cables shorter than 500 ft. do not need to be a shock hazard. A tester designed to test larger assemblies at higher currents can still be a hazard with wrong settings or if it malfunctions. IEC479-1 and EN61010-1:1993 specify a non-hazardous energy source as being less than 45 micro coulombs (this is 45 / 1500 = .03 micro-farads at 1500 VDC). This limit includes energy from both the tester and the assembly under test.
Which wires require testing	Test voltages must be applied between all relevant combinations of wires, including shields, to test insulation.
Voltage Ramp Rate in DC testing	Controlling the voltage ramp rate is a common way to limit the current needed to bring each wire up to the hipot voltage. A modern hipot tester can limit the inrush current and detect failures as the voltage is rising which makes the ramp rate specification unnecessary.
Burning out shorts and arcing	A high-voltage test that allows high currents causing visible arcing that burns out a short and then passes the wired assembly as good, cannot be relied upon for defect removal because carbon tracks and potential insulation damage may occur.
Voltage accuracy	Voltage accuracy must be within 10 percent or a higher voltage setting must be used that assures testing to within 10 percent of the specified test voltage.
Finding stray strands	High-voltage testing, unless done at many thousands of volts, does not detect stray strands unless they are within .050 of an inch of another conductor/contact.

MAGNETO-MECHANICAL MEASUREMENTS FOR HIGH CURRENT APPLICATIONS

Jack Ekin, NIST – Electromagnetics Division

GOALS

This project specializes in measurements of the effect of mechanical strain on superconductor properties such as critical-current density for applications in magnetics, power transmission, and electronics. Recent research has produced the first electromechanical data for the new class of high-temperature coated conductors, one of the few new technologies expected to have an impact on the electric-power industry. The Strain Scaling Law, previously developed by the project for predicting the axial-strain response of low-temperature superconductors in high magnetic fields, is now being generalized to three-dimensional stresses, for use in finite-element design of magnet structures, and to high-temperature superconductors. Recent research includes extending the high-magnetic-field limits of electromechanical measurements for development of nuclear-magnetic-resonance (NMR) spectrometers operating at 23.5 teslas and 1 gigahertz, and the next generation of accelerators for high-energy physics. The project has diversified its research to include magnetoresistance studies on a new class of carbon nanostructures using our highfield superconducting magnet facility and a newly developed, variable-angle, variable-temperature measurement capability.

CUSTOMER NEEDS

The project serves industry primarily in two areas. First is the need to develop a reliable measurement capability in the severe environment of superconductor applications: low temperature, high magnetic field, and high stress. The data are being used, for example, in the design of superconducting magnets for the magnetic-resonance-imaging (MRI) industry, which provides invaluable medical data for health care, and contributes 2 billion dollars per year to the U.S. economy.

The second area is to provide data and feedback to industry for the development of high-performance superconductors. This is especially exciting because of the recent deregulation of the electric power utilities and the attendant large effort being devoted to develop superconductors for power conditioning and enhanced power-transmission capability. We receive numerous requests, from both industry and government agencies, for reliable electromechanical data to help guide their efforts in research and development in this critical growth period.

The recent success of the second generation of high-temperature superconductors has brought with it new measurement problems in handling these brittle conductors. We have the expertise and equipment to address these problems. Stress and strain management is one of the key parameters needed to move the second-generation high-temperature coated conductors to the market place. The project utilizes the expertise and unique electromechanical measurement facilities at NIST to provide performance feedback and engineering data to companies and national laboratories fabricating these conductors in order to guide their decisions at this critical phase of coated-conductor development.

TECHNICAL STRATEGY

Our project has a long history of unique measurement service in the specialized area of electromechanical metrology. Significant emphasis is placed on an integrated approach. We provide industry with first measurements of new materials, specializing in cost-effective testing at currents less than 1000 amperes. Consultation is also provided to industry on developing its own measurements for routine testing. We also provide consultation on metrology to the magnet industry to predict and test the performance of very large cables with capacities on the order of 10 000 amperes, based on our tests at smaller scale. In short, our strategy has consistently been to sustain a small, well connected team approach with industry.

Electromechanical Measurements of Superconductors – We have developed an array of specialized measurement systems to test the effects of mechanical stresses on the electrical performance of superconducting materials. The objective is to simulate the operating conditions to which a superconductor will be subjected in magnet applications. In particular, since most technologically important superconductors are brittle, we need to know the value of strain at which fractures occur in the superconductor. This value is referred to as the irreversible strain limit, since the damage caused by the formation of cracks is permanent. The effect of cracks is extrinsic. In contrast, below the irreversible strain, there exists an elastic strain regime where the effect of strain is intrinsic to the superconductor. In this elastic regime, the variation in the critical-current density (Jc) with strain, if any, is reversible and is primarily associated with changes in the superconductor's fundamental properties, such as the critical temperature (Tc) and the upper critical field (Hc2), as well as changes in the superconductor's microstructure due to the application of strain.

Measurement Facilities – Extensive, advanced measurement facilities are available, including high-field (18.5 teslas) and split-pair magnets, servohydraulic mechanical testing systems, and state-of-the-art measurement probes. These probes are used for research on the effects of axial tensile strain and transverse compressive strain on critical current; measurement of cryogenic stress-strain characteristics; composite magnetic coil testing; and variable-temperature magnetoresistance measurements. Our electromechanical test capability for superconductors is one of the few of its kind in the world, and the only one providing specialized measurements for U.S. superconductor manufacturers.

Collaboration with Other Government Agencies – These measurements are an important element of our ongoing work with the U.S. Department of Energy **(DOE)**. The DOE

Office of High Energy Physics sponsors our research on electromechanical properties of candidate superconductors for particle-accelerator magnets. These materials include low-temperature superconductors (Nb3Sn, Nb3Al, and MgB2), and high-temperature superconductors – Bi-Sr-Ca-Cu-O **(BSCCO)** and Y-Ba-Cu-O **(YBCO)** – including conductors made on rolling-assisted, biaxially textured substrates **(RABiTS)** and conductors made by ion-beam-assisted deposition **(IBAD)**. The purpose of the database produced from these measurements is to allow the magnet industry to design reliable superconducting magnet systems. Our research is also sponsored by the DOE Office of Electric Transmission and Distribution. Here, we focus on high-temperature superconductors for power applications, including power-conditioning systems, motors and generators, transformers, magnetic energy storage, and transmission lines. In all these applications, the electromechanical properties of these inherently brittle materials play an important role in determining their successful utilization.

Scaling Laws for Magnet Design – In the area of low-temperature superconductors, we have embarked on a fundamental program to generalize the Strain Scaling Law **(SSL)**, a magnet design relationship we discovered two decades ago. Since then, the SSL has been used in the structural design of most large magnets based on superconductors with the A-15 crystal structure. However, this relationship is a one-dimensional law, whereas magnet design is three-dimensional. Current practice is to generalize the SSL by assuming that distortional strain, rather than hydrostatic strain, dominates the effect. Recent measurements in our laboratory suggest however that this assumption is invalid. We are now developing a measurement system to carefully determine the three-dimensional strain effects in A-15 superconductors. The importance of these measurements for very large accelerator magnets is considerable. The Strain Scaling Law is now also being developed for high-temperature superconductors since we recently discovered that practical high-temperature superconductors exhibit an intrinsic axial-strain effect.

ACCOMPLISHMENTS

• New Measurement Method for Marginally Stable Superconductor Wires – The next generation of particle accelerators for high-energy physics, and magnet systems for nuclear magnetic resonance (NMR) spectroscopy, will require the development of a new type of superconducting niobium-tin wire able to carry extremely high currents at high magnetic fields. One way to achieve high currents is to push the density of superconductor filaments in composite wires to new limits. Oxford Superconductor Technology (Carteret, NJ) has successfully demonstrated the feasibility of this concept. However, this could significantly reduce the beneficial "pre-compressive strain" in these conductors upon cooling, an important parameter for magnet design. Our superconductor electromechanical testing system is the only one in the U.S. that utilizes stress-free cooling, which is essential for a direct measurement of pre-compressive strain. Unfortunately, the new niobium-tin wires, owing to their relatively small amount of copper stabilizer, are only marginally stable, which makes electrical characterization extremely challenging. Hence, a new measurement technique was required that did not compromise the stress-free cooling advantage.

Pre-compressive strain ε_{max} versus Nb fraction for several niobium-tin wires with high niobium density. Data were obtained using a new measurement method developed by EEEL researchers for marginally stable superconductor wires.

The technique consists of measuring critical-current density (the maximum lossless current density that a superconductor can carry) versus axial strain for a number of copper-plated specimens of the same wire with different amounts of copper. We then deduced the strain properties of the virgin (noncopper-plated) wire by an extrapolation technique. Copper plating made the niobium-tin wires electrically stable enough to characterize, but the extra copper also influenced the value of the pre-compressive strain (ε_{max}); hence the need for extrapolation. We confirmed that ε_{max} indeed decreased linearly with increasing niobium fraction. However, we found that other parameters such as the matrix material and wire diameter also influence ε_{max}.

The pre-compressive strain for high-niobium-fraction wires can be reduced to about 0.1 percent, a very small strain window for magnet design. Fortunately, we also found that the use of copper alloys, instead of pure copper – along with small wire diameters – substantially mitigates the problem and provides reasonable strain operating margins in these high performance conductors. The data were used by Oxford Superconductor Technology to make immediate decisions regarding the conductor design for a new NMR system.

• Copper Stabilizer Improves Coated Superconductors' Strain Tolerance – High-temperature superconductor **(HTS)** wires are now being fabricated in kilometer lengths, providing the basis for a new generation of electric power devices, including high power-density motors and generators, transmission lines, and power conditioners. The development of HTS technology is expected to play a crucial role in maintaining the reliability of the power grid and upgrading power delivery to core urban areas. The most promising superconductor candidate for replacing ageing utility equipment is the highly textured Y-Ba-Cu-O **(YBCO)** compound deposited on buffered flexible metallic substrates. These "coated conductors" have a much higher current-carrying capacity compared to the Bi-Sr-Ca-Cu-O **(BSCCO)** tapes now commercially available. Whereas BSCCO tapes experience permanent damage when subjected to axial strains less than 0.2 percent, we demonstrated last year that the formation of cracks in the new YBCO system does not commence until subjected to strains higher than 0.38 percent, almost a two-fold increase in strain tolerance. This resilience of YBCO to strain is providing a strong motivation to produce commercial lengths of this "second generation" conductor, especially for the design of electric generators for which strain tolerance requirements have been raised to 0.4 percent.

This year, we found that adding a Cu layer to the YBCO coated-conductor architecture extends the irreversible strain limit (eirr) of this composite even further, from 0.38 percent to more than 0.5 percent. This markedly widens the strain window for coated-conductor applications and takes it beyond even the most demanding benchmark for large-scale superconducting generators. These measurements were undertaken in close collaboration with conductor manufacturers American Superconductor (Westborough, MA) and SuperPower (Schenectady, NY), who are incorporating the stabilizer layers either by Cu-lamination or Cu-plating. The original motivation for adding the Cu layers was to improve the electric and thermal stability of the conductor; the strain-tolerance dividend was unexpected. We can relate this remarkable result to the mismatch of thermal contraction between Cu and the other components of the composite. During sample cooling from processing temperatures to the cryogenic operating temperatures, the Cu layer exerts an additional pre-compressive strain on the YBCO film, and hence extends the irreversible strain E_{irr} where permanent damage occurs. The Cu may also be acting as a crack arrester, which further improves the strain tolerance.

Normalized critical current density as a function of mechanical tensile strain for unlaminated and Culaminated YBCO coated conductor. The Cu stabilization layer extends the irreversible strain limit ε_{irr} of the composite from 0.38 percent to more than 0.5 percent.

Photograph of a new magnetoresistance probe designed to investigate carbon nanostructures. At the right end of the probe, the photo shows the steppermotor-controlled worm-gear system and sample stage, which allow precise angle-dependent, high-field measurements.

• **New Magnetoresistance Apparatus to Probe Carbon Nanostructures** – Electronic properties of materials change markedly as their dimensions approach those of a few atomic layers. Carbon nanostructures (including graphite sheets, single-walled carbon nanotubes, and multi-walled carbon nanotubes) are prime examples of such potentially useful materials, although some of their very fundamental properties remain controversial. Characterization of these structures at high magnetic fields is one of the principal methods for determining the existence of ballistic conduction, for example, which could be the foundation for a new generation of nanoelectronic devices.

We have designed and recently commissioned an apparatus to measure magnetoresistance of these highly directional structures in fields up to 18.5 teslas. (For comparison, the earth's magnetic field is only about 0.05 millitesla.) The apparatus automatically acquires data as a function of magneticfield magnitude, angle, and temperature. It was designed to also be compatible with the very-highfield magnet facilities at the National High Magnetic Field Laboratory at Florida State University, permitting the extension of EEEL's measurements to fields up to 30 teslas. Magnetic field mapping has commenced for nanotubes fabricated at NIST and Rice University as well as for graphitic sheet structures manufactured by a nanotechnology research team at Georgia Institute of Technology. Magnetic-field angle can be varied with a resolution of better than 0.1 degree over a range of 130 degrees, and sample temperature can be varied over an extended range of 4.1 to 120 kelvins, with a stability of better than 3 millikelvins at 4.2 kelvins.

• **Textbook on Cryogenic Measurement Apparatus and Methods** – A new textbook has been written on experimental techniques for cryogenic measurements to be published by Oxford University Press. It covers the design of cryogenic measurement probes and provides cryogenic materials data for their construction. Topics include thermal techniques for designing a cryogenic apparatus, selecting materials appropriate for such apparatus, how to make high-quality electrical contacts to a superconductor, and how to make reliable criticalcurrent measurements. The textbook is written for beginning graduate students, industry measurement engineers, and materials scientists interested in learning how to design successful low-temperature measurement systems. The appendices are written for experts in the field of cryogenic measurements and include electrical, thermal, magnetic, and mechanical properties of technical materials for cryostat construction; properties of cryogenic liquids; and temperature measurement tables and thermometer properties. These appendices aim to collect in one place many of the data essential for designing new cryogenic measurement apparatus.

ISOLATION TECHNOLOGIES FOR RELIABLE INDUSTRIAL MEASUREMENTS

National Instruments Corporation

OVERVIEW

Voltage, current, temperature, pressure, strain, and flow measurements are an integral part of industrial and process control applications. Often, these applications involve environments with hazardous voltages, transient signals, common-mode voltages, and fluctuating ground potentials capable of damaging measurement systems and ruining measurement accuracy. To overcome these challenges, measurement systems designed for industrial applications make use of electrical isolation. This white paper focuses on isolation for analog measurements, provides answers to common isolation questions, and includes information on different isolation implementation technologies.

UNDERSTANDING ISOLATION

Isolation electrically separates the sensor signals which can be exposed to hazardous voltages (Hazardous Voltages are greater than 30 Vrms, 42.4 Vpk or 60 VDC), from the measurement system's low-voltage backplane. Isolation offers many benefits including:

- Protection for expensive equipment, the user, and data from transient voltages
- Improved noise immunity
- Ground loop removal
- Increased common-mode voltage rejection

Isolated measurement systems provide separate ground planes for the analog front end and the system backplane to separate the sensor measurements from the rest of the system. The ground connection of the isolated front end is a floating pin that can operate at a different potential than the earth ground. Figure 1 represents an analog voltage measurement device. Any common-mode voltage that exists between the sensor ground and the measurement system ground is rejected. This prevents ground loops from forming and removes any noise on the sensor lines.

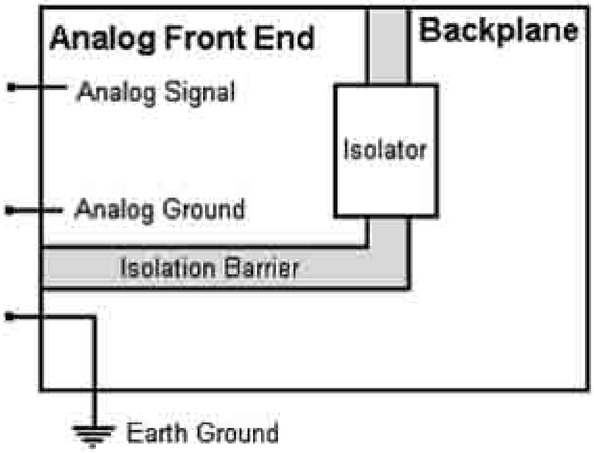


Figure 1. Bank Isolated Analog Input Circuitry

NEED FOR ISOLATION

Consider isolation for measurement systems that involve any of the following:

- Vicinity to hazardous voltages
- Industrial environments with possibility of transient voltages
- Environments with common mode voltage or fluctuating ground potentials
- Electrically noisy environments such as those with industrial motors
- Transient sensitive applications where it is imperative to prevent voltage spikes from being transmitted through the measurement system

Industrial measurement, process control, and automotive test are examples of applications where common-mode voltages, high voltage transients, and electrical noise are common. Measurement equipment with isolation can offer reliable measurements in these harsh environments. For medical equipment in direct contact with patients, isolation is useful in preventing power line transients from being transmitted through the equipment.

Based on your voltage and data rate requirements, you have several options for making isolated measurements. You can use plug-in boards for laptops, desktop PCs, industrial PCs, PXI, Panel PCs, and CompactPCI with the option of built-in isolation or external signal conditioning. Isolated measurements can also be made using programmable automation controllers (PACs) and measurement systems for USB.

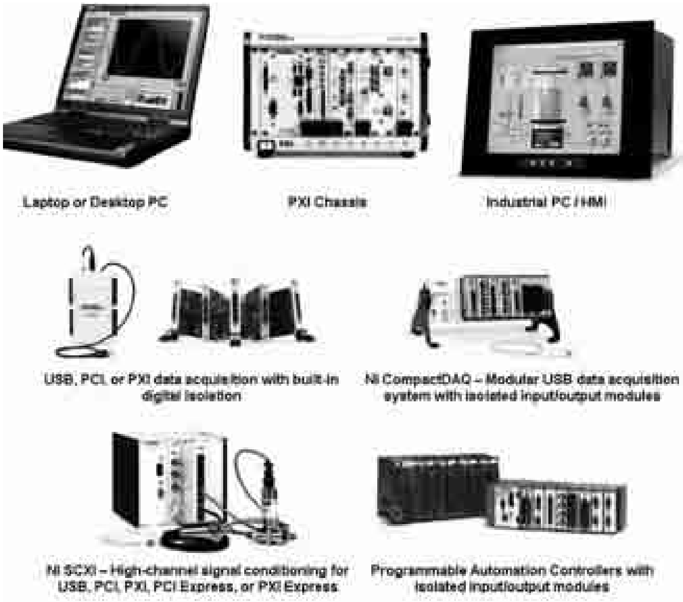

Laptop or Desktop PC
PXI Chassis
Industrial PC / HMI
USB, PCI, or PXI data acquisition with built-in digital isolation
NI CompactDAQ – Modular USB data acquisition system with isolated input/output modules
NI SCXI – High-channel signal conditioning for USB, PCI, PXI, PCI Express, or PXI Express
Programmable Automation Controllers with isolated input/output modules

Figure 2. Isolated Data Acquisition Systems

METHODS OF IMPLEMENTING ISOLATION

Isolation requires signals to be transmitted across an isolation barrier without any direct electrical contact. Light emitting diodes (LEDs), capacitors, and inductors are three commonly available components that allow electrical signal transmission without any direct contact. The principles on which these devices are based form the core of the three most common technologies for isolation – optical, capacitive, and inductive coupling.

OPTICAL COUPLING

LEDs produce light when a voltage is applied across them. Optical isolation uses an LED along with a photo-detector device to transmit signals across an isolation barrier using light as the method of data translation. A photo-detector receives the light transmitted by the LED and converts it back to the original signal.

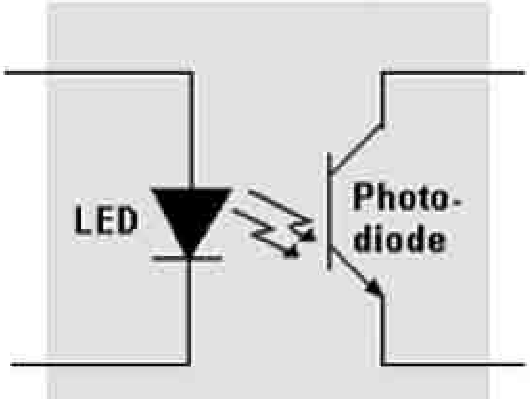


Figure 3. Optical Coupling

Optical isolation is one of the most commonly used methods for isolation. One benefit of using optical isolation is its immunity to electrical and magnetic noise. Some of the disadvantages include transmission speed, which is restricted by the LED switching speed, high-power dissipation, and LED wear.

CAPACITIVE COUPLING

Capacitive isolation is based on an electric field that changes based on the level of charge on a capacitor plate. This charge is detected across an isolation barrier and is proportional to the level of the measured signal.

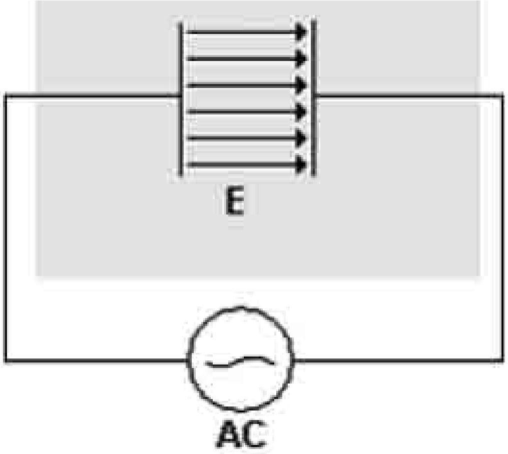


Figure 4. Capacitive Isolation

One advantage of capacitive isolation is its immunity to magnetic noise. Compared to optical isolation, capacitive isolation can support faster data transmission rates because there are no LEDs that need to be switched. Since capacitive coupling involves the use of electric fields for data transmission, it can be susceptible to interference from external electric fields.

INDUCTIVE COUPLING

In the early 1800s, Hans Oersted, a Danish physicist, discovered that current through a coil of wire produces a magnetic field. It was later discovered that current can be induced in a second coil by placing it in close vicinity of the changing magnetic field from the first coil. The voltage and current induced in the second coil depend on the rate of current change through the first. This principle is called mutual induction and forms the basis of inductive isolation.

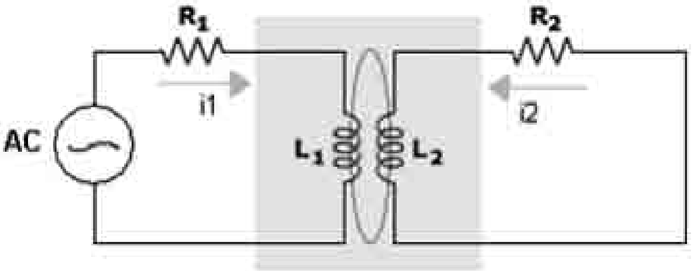


Figure 5. Inductive Coupling

Inductive isolation uses a pair of coils separated by a layer of insulation. Insulation prevents any physical signal transmission. Signals can be transmitted by varying current flowing through one of the coils, which causes a similar current to be induced in the second coil across the insulation barrier. Inductive isolation can provide high-speed transmission similar to capacitive techniques. Because inductive coupling involves the use of magnetic fields for data transmission, it can be susceptible to interference from external magnetic fields.

ANALOG ISOLATION AND DIGITAL ISOLATION

Several commercial off-the-shelf (COTS) components are available today, many of which incorporate one of the above technologies to provide isolation. For analog input/output channels, isolation can be implemented either in the analog section of the board, before the analog-to-digital converter (ADC) has digitized the signal (analog isolation) or after the ADC has digitized the signal (digital isolation). Different circuitry needs to be designed around one of these techniques based on the location in the circuit where isolation is being implementing. You can choose analog or digital isolation based on your data acquisition system performance, cost, and physical requirements. Figure 6 shows the different stages of implementing isolation.

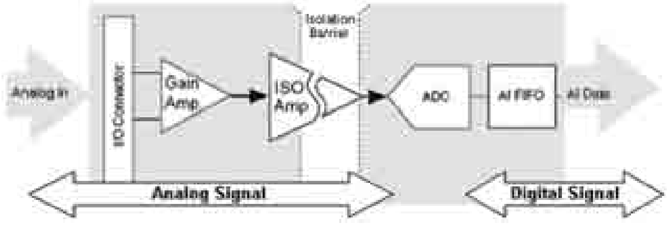


Figure 6a. Analog Isolation

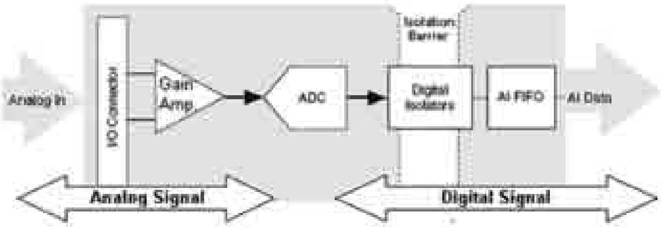


Figure 6b. Digital Isolation

The following sections cover analog and digital isolation in more detail and explore the different techniques for implementing each.

ANALOG ISOLATION

The isolation amplifier is generally used to provide isolation in the analog front end of data acquisition devices. "ISO Amp" in Figure 6a represents an isolation amplifier. The isolation amplifier in most circuits is one of the first components of the analog circuitry. The analog signal from a sensor is passed to the isolation amplifier, which provides isolation and passes the signal to the analog-to-digital conversion circuitry. Figure 7 represents the general layout of an isolation amplifier.

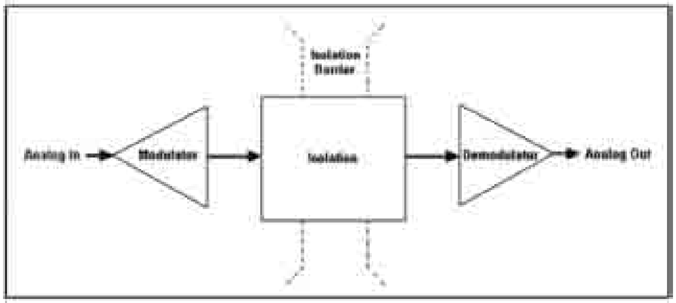


Figure 7. Isolation Amplifier

In an ideal isolation amplifier, the analog output signal is the same as the analog input signal. The section labeled "isolation" in Figure 7 uses one of the techniques discussed in the previous section (optical, capacitive, or inductive coupling) to pass the signal across the isolation barrier. The modulator circuit prepares the signal for the isolation circuitry. For optical methods, this signal needs to be digitized or translated into varying light intensities. For capacitive and inductive methods, the signal is translated into varying electric or magnetic fields. The demodulator circuit then reads the isolation circuit output and converts it back into the original analog signal.

Because analog isolation is performed before the signal is digitized, it is the best method to apply when designing external signal conditioning for use with existing non-isolated data acquisition devices. In this case, the data acquisition device performs the analog-to-digital conversion and the external circuitry provides isolation. With the data acquisition device and external signal conditioning combination, measurement system vendors can develop general-purpose data acquisition devices and sensor-specific signal conditioning. Figure 8 shows analog isolation being implemented with flexible signal conditioning that uses isolation amplifiers. Another benefit to isolation in the analog front end is protection for the ADC and other analog circuitry from voltage spikes.

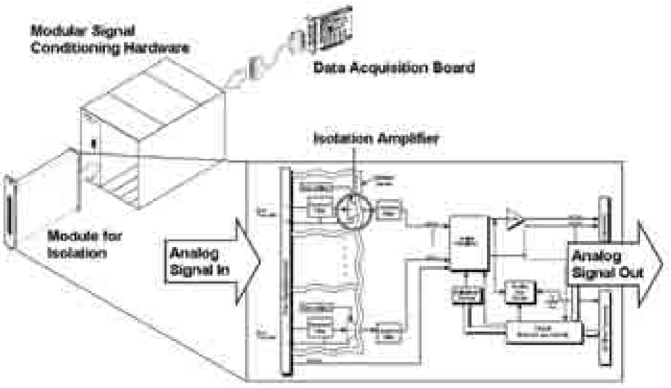


Figure 8. Use of Isolation Amplifiers in Flexible Signal Conditioning Hardware

There are several options available on the market for measurement products that use a general-purpose data acquisition device and external signal conditioning. For example, the National Instruments M Series includes several non-isolated, general-purpose multifunction data acquisition devices that provide high-performance analog I/O and digital I/O. For applications that need isolation, you can use the NI M Series devices with external signal conditioning, such as the National Instruments SCXI or SCC modules. These signal conditioning platforms deliver the isolation and specialized signal conditioning needed for direct connection to industrial sensors such as load cells, strain gages, pH sensors, and others.

DIGITAL ISOLATION

Analog-to-digital converters are one of the key components of any analog input data acquisition device. For best performance, the input signal to the analog-to-digital converter should be as close to the original analog signal as possible. Analog isolation can add errors such as gain, non-linearity and offset before the signal reaches the ADC.

Placing the ADC closer to the signal source can lead to better performance. Analog isolation components are also costly and can suffer from long settling times. Despite better performance of digital isolation, one of the reasons for using analog isolation in the past was to provide protection for the expensive analog-to-digital converters. As ADC prices have significantly declined, measurement equipment vendors are choosing to trade ADC protection for better performance and lower cost offered by digital isolators (see Figure 9).

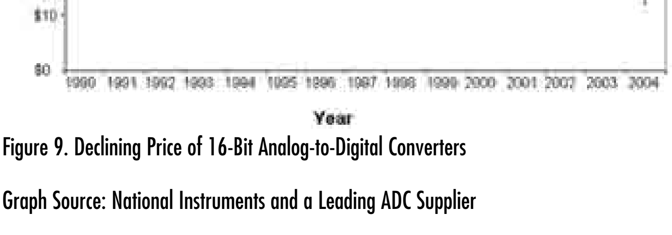


Figure 9. Declining Price of 16-Bit Analog-to-Digital Converters

Graph Source: National Instruments and a Leading ADC Supplier

Compared to isolation amplifiers, digital isolation components are lower in cost and offer higher data transfer speeds.

Digital isolation techniques also give analog designers more flexibility to choose components and develop optimal analog front ends for measurement devices. Products with digital isolation use current- and voltage-limiting circuits to provide ADC protection. Digital isolation components follow the same fundamental principles of optical, capacitive, and inductive coupling that form the basis of analog isolation.

Leading digital isolation component vendors such as Avago Technologies, Texas Instruments and Analog Devices have developed their isolation technologies around one of these basic principles. Avago Technologies offers digital isolators based on optical coupling, Texas instruments bases its isolators on capacitive coupling, and Analog Devices isolators use inductive coupling.

OPTOCOUPLERS

Optocouplers, digital isolators based on the optical coupling principles, are one of the oldest and most commonly used methods for digital isolation. They can withstand high voltages and offer high immunity to electrical and magnetic noise. Optocouplers are often used on industrial digital I/O products, such as the National Instruments PXI-6514 isolated digital input/output board (see Figure 10) and National Instruments PCI-7390 industrial motion controller.

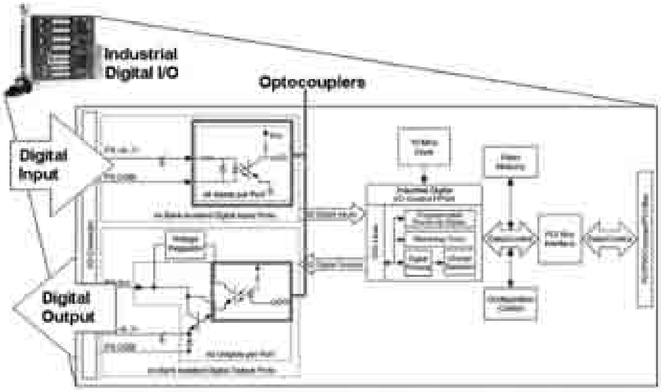


Figure 10. Industrial Digital I/O Products Use Optocouplers

For high-speed analog measurements, optocouplers, however, suffer from speed, power dissipation, and LED ware limitations associated with optical coupling. Digital isolators based on capacitive and inductive coupling can alleviate many optocoupler limitations.

CAPACITIVE ISOLATION

Texas Instruments offers digital isolation components based on capacitive coupling. These isolators provide high data transfer rates and high transient immunity. Compared to capacitive and optical isolation methods inductive isolation offers lower power consumption.

INDUCTIVE ISOLATION

iCoupler technology, introduced by Analog Devices in 2001, uses inductive coupling to offer digital isolation for high-speed and high-channel-count applications. iCouplers can provide 100 Mb/s data transfer rates with 2,500 V isolation withstand; for a 16-bit analog measurement system that implies sampling rates in the mega hertz range. Compared to optocouplers, iCouplers offer other benefits such as reduced power consumption, high operating temperature range up to 125°C, and high transient immunity up to 25 kV/ms.

iCoupler technology is based on small, chip-scale transformers. An iCoupler has three main parts – a transmitter, transformers, and a receiver. The transmitter circuit uses edge trigger encoding and converts rising and falling edges on the digital lines to 1 ns pulses. These pulses are transmitted across the isolation barrier using the transformer and decoded on the other side by the receiver circuitry (see Figure 11). The small size of the transformers, about three-tenths of a millimeter, makes them practically impervious to external magnetic noise. iCouplers can also lower measurement hardware cost by integrating up to four isolated channels per integrated circuit (IC) and, compared to optocouplers, they require fewer external components.

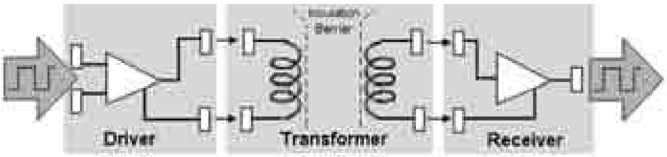


Figure 11. Induction Coupling-Based iCoupler Technology from Analog Devices

Source: Analog Devices

Measurement hardware vendors are using iCouplers to offer high-performance data acquisition systems at lower costs.

National Instruments industrial data acquisition devices intended for high-speed measurements, such as the isolated M Series multifunction data acquisition devices, use iCoupler digital isolators (see Figure 12). These devices provide 60 VDC continuous isolation and 1,400 Vrms/1,900 VDC channel-to-bus isolation withstand for 5 s on multiple analog and digital channels and support sampling rates up to 250 kS/s. National Instruments C Series modules used in the NI PAC platform, NI CompactRIO, NI CompactDAQ, and other high-speed NI USB devices also use the iCoupler technology.

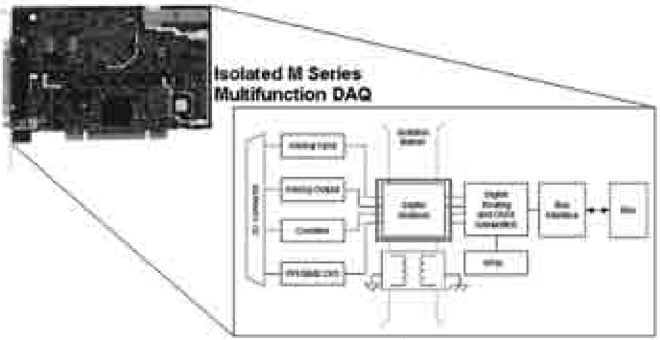
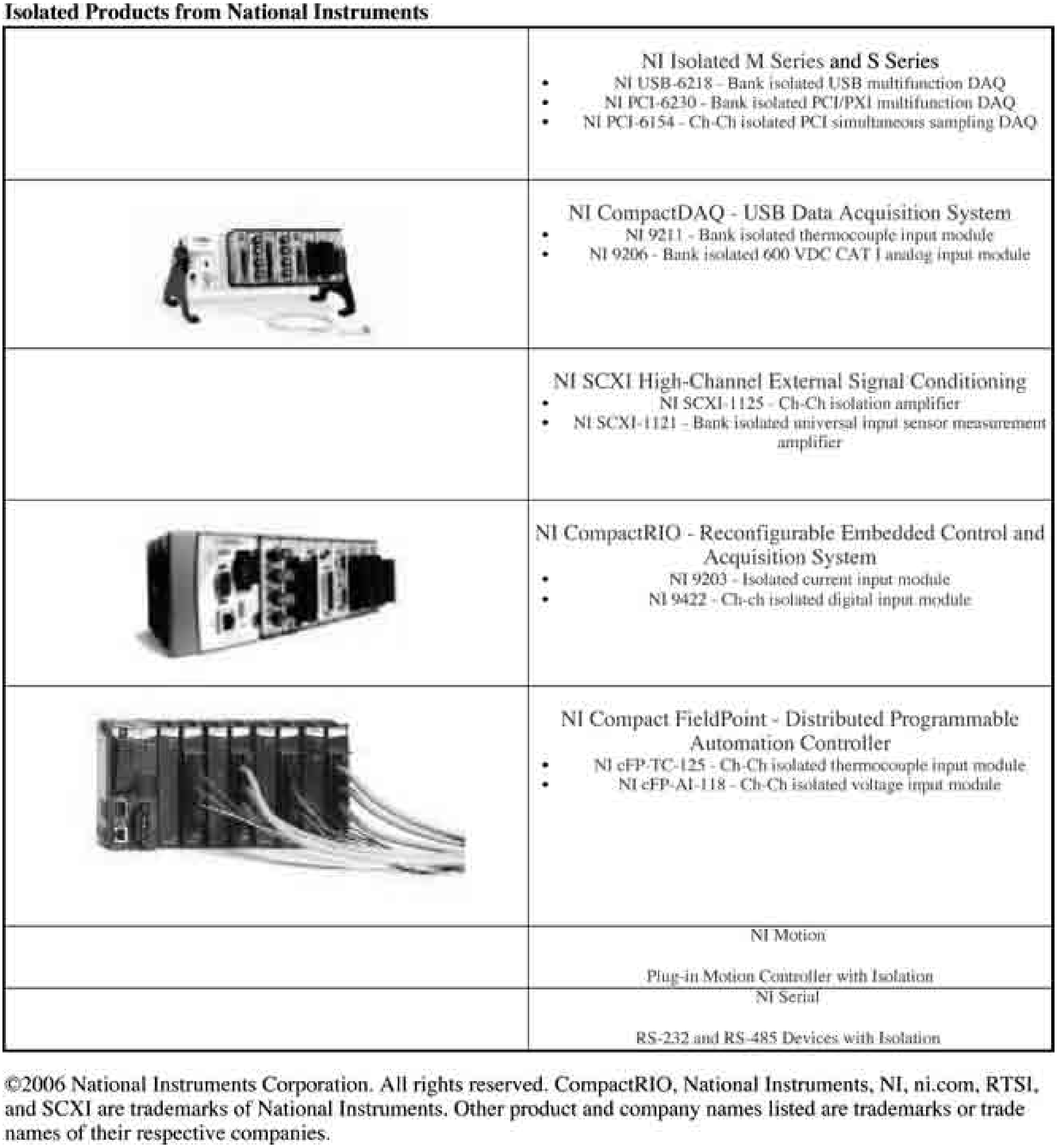


Figure 12. National Instruments Isolated M Series Multifunction DAQ Uses

SUMMARY

Isolated data acquisition systems can provide reliable measurements for harsh industrial environments with hazardous voltages and transients. Your need for isolation is based on your measurement application and surrounding environments. Applications that require connectivity to different specialty sensors using a single, general-purpose data acquisition device can benefit from external signal conditioning with analog isolation, whereas applications needing lower-cost, high-performance analog inputs benefit from measurement systems with digital isolation technologies.



Isolated Products from National Instruments

	NI Isolated M Series and S Series • NI USB-6218 - Bank isolated USB multifunction DAQ • NI PCI-6230 - Bank isolated PCI/PXI multifunction DAQ • NI PCI-6154 - Ch-Ch isolated PCI simultaneous sampling DAQ
	NI CompactDAQ - USB Data Acquisition System • NI 9211 - Bank isolated thermocouple input module • NI 9206 - Bank isolated 600 VDC CAT I analog input module
	NI SCXI High-Channel External Signal Conditioning • NI SCXI-1125 - Ch-Ch isolation amplifier • NI SCXI-1121 - Bank isolated universal input sensor measurement amplifier
	NI CompactRIO - Reconfigurable Embedded Control and Acquisition System • NI 9203 - Isolated current input module • NI 9422 - Ch-ch isolated digital input module
	NI Compact FieldPoint - Distributed Programmable Automation Controller • NI cFP-TC-125 - Ch-Ch isolated thermocouple input module • NI cFP-AI-118 - Ch-Ch isolated voltage input module
	NI Motion Plug-in Motion Controller with Isolation
	NI Serial RS-232 and RS-485 Devices with Isolation

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FALL-OF-POTENTIAL GROUND TESTING, CLAMP-ON GROUND TESTING COMPARISON

Chauvin Arnoux, Inc.

On April 14, 2002, a ground resistance test was conducted to compare the results obtained from the Fall-of-Potential 3-Point testing method to the clamp-on testing method. The grounding system consisted of four copper clad rods installed in an approximate 20 ft square. Three of the rods are 5/8" in diameter and 10 ft in length. The fourth rod is 1/2" in diameter and 8 ft in length. All rods were coupled together with 3-gauge aluminum wire. Figure 1 shows the schematic of the system.

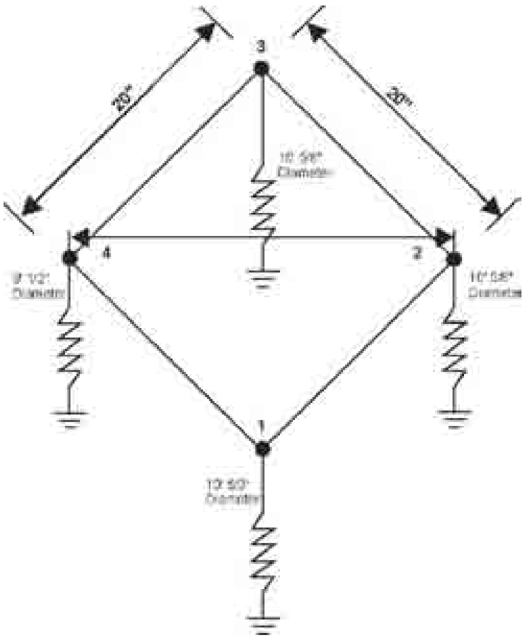


Figure 1. The Grounding System

The tests were conducted with the following equipment manufactured by AEMC instrument:

- Model 4500, 4-Point Ground Resistance Tester
- Model 4630, 4-Point Ground Resistance Tester
- Model 3731, Clamp-On Ground Resistance Tester.

Additionally, we used the AEMC Model 5600, a micro-ohmmeter to verify the bonding of the aluminum wire to the individual ground rods.

The soil conditions in the test area were predominately loam with some gravel. Conditions on the day of the test were dry and sunny, some light rain had occurred the previous day to the test. Therefore, the soil was somewhat moist at the surface.

The AEMC Model 5600 Micro-Ohmmeter was used to measure bonding resistance at each rod and was the first test completed. Measurements from each conductor to the rod were taken as well as measurements from conductor to conductor through the rod and clamp. Readings on rod number three ranged from 615 to 733mΩ at each bonding point, indicating that all connections were good. See Figure 2 for full results.

Measurement Point	Resistance (µOhms)
A to B	713
C to B	615
A to C	733

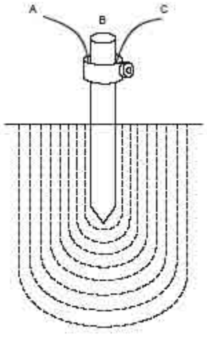


Figure 2. Bonding resistance measurements

In the first test, the AEMC Model 4500 was used as 3-Point ground tester. Rod number three was first disconnected from the other rods in the system so that its individual resistance could be measured. The X lead was attached to rod number three (see Figure 3). The Z lead was attached to an auxiliary electrode 100 feet away and the Y lead was initially connected to the auxiliary electrode 60 feet away. Readings were taken with the Y electrode at 90, 80, 70, 60, 50, 40, 30, 20 and 10 feet. Figure 3 shows the results of this test.

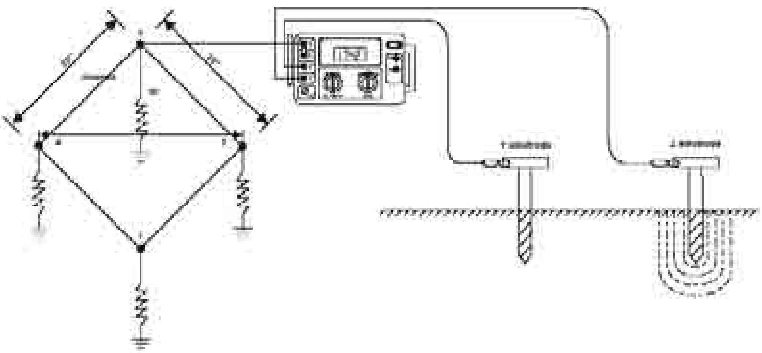
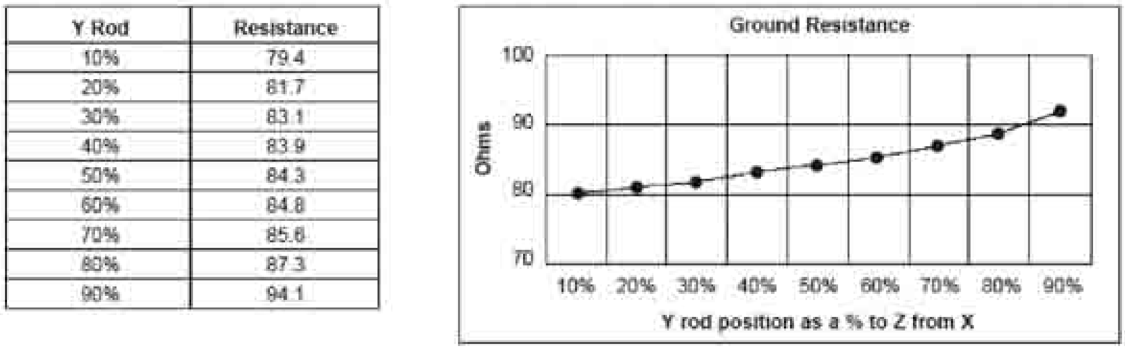


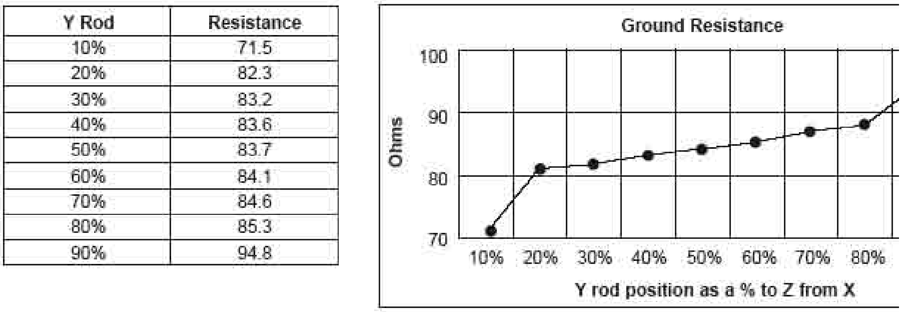
Figure 3. Three-Point test connection



Y Rod	Resistance
10%	79.4
20%	81.7
30%	83.1
40%	83.9
50%	84.3
60%	84.8
70%	85.6
80%	87.3
90%	94.1

Figure 4. Model 4500 test results

The same test was repeated using the AEMC Model 4630 fall-of-potential ground tester. The results are shown in Figure 5.

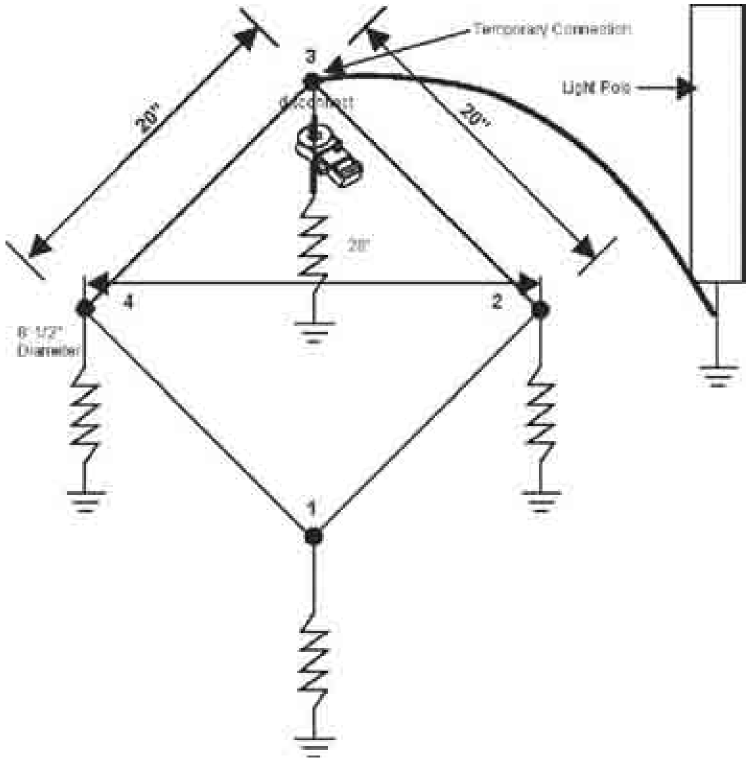


Y Rod	Resistance
10%	71.5
20%	82.3
30%	83.2
40%	83.6
50%	83.7
60%	84.1
70%	84.6
80%	85.3
90%	94.8

Figure 5. Model 4630 test results

Finally, the AEMC Model 3731 was used to measure the resistance at rod number three with all other rods detached from it. A temporary cable was installed between rod number three and the municipal grounding system, thus setting up the required parallel paths necessary for accurate measurement using a clamp-on ground tester (see Figure 6). Under these conditions, the reading was 84.5Ω.

The results of these tests showed that the clamp-on ground tester is indeed an effective tool in measuring ground resistance when used under the proper conditions. Readings between the clamp-on ground testing and the fall-of-potential ground testing method correlate. The advantages of using the clamp-on tester were the ability to test without disconnecting the rod from service and the ability to test without the need for auxiliary ground electrodes. These two points saved considerable amount of time in conducting the test



INLINE DETECTION, ANALYSIS FIND INVISIBLE ELECTRICAL DEFECTS FASTER

Michael Schmidt, Hyoung Kang and Larry Dworkin, FEI Co., Hillsboro, Oregon; Kenneth Harris and Sherry Lee, PDF Solutions, San Jose

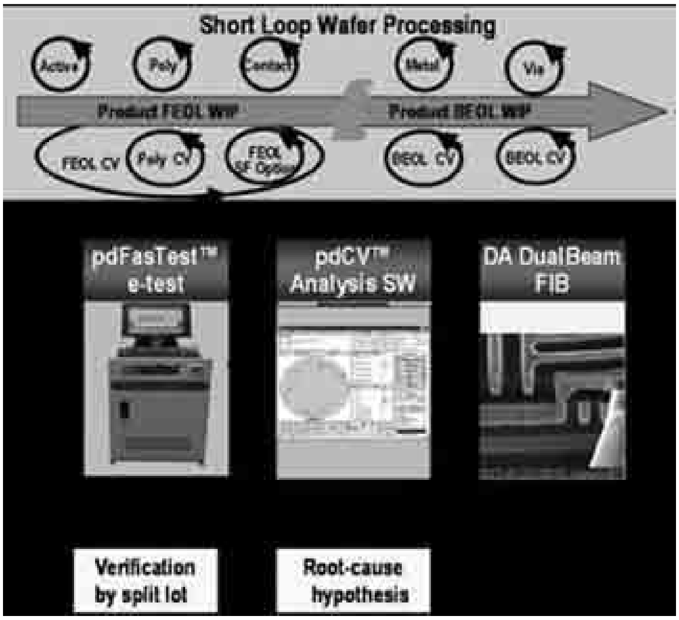
From a yield perspective, the only defects that truly matter are those that affect product yield. The rest are just a nuisance and any time spent on them is wasted time. Most inline inspection and defect detection methods are focused on visual defects, which may or may not affect performance. Correlation with product yield is generally not possible until electrical test data becomes available after processing is complete. Of course, we have learned to make pretty good guesses about which visual defects are important and which are not based on composition and morphology. However, as devices become smaller and new processes introduce new structures and materials, an increasing fraction of killer defects are non-visual — invisible to conventional inline inspection technologies. They are primarily found only by electrical testing days or weeks after they occur.

To address these shortcomings, a new inline detection methodology has been developed that detects non-visual electrical defects 10 times sooner than conventional approaches.1 In addition, it provides electrical data that may be correlated with visual defects to aid in discriminating the killer defects from the nuisance defects. Faster defect detection and root-cause analysis has been shown to shorten process development and yield learning cycles, accelerate the ramp to volume, and speed recovery from yield excursions, bringing new products to market sooner and enhancing yield and profitability in high-volume production.

Visual defect detection methods are fast and can be performed on product wafers at almost any point in the manufacturing process. In comparison, conventional approaches to non-visual defect detection are limited in several ways:

- They typically rely on electrical tests of product wafers or SRAM test structures, followed by intensive visual investigation and off-line failure analysis.
- They can only be applied late in the manufacturing process.
- The defects they detect can be difficult to relocate and analyze on the product wafer or test structure.
- SRAM test structures may not be sufficiently sensitive to capture small defects.
- They require a large number of wafers to provide statistically significant results at the few ppb level required to assure stable yields at 90 nm and beyond.
- Failure analysis in a lab outside the fab can take many days.

The new technique addresses these limitations.2 It combines fast, in-fab electrical testing on specially designed short-flow test wafers with automated focused ion beam (FIB) and scanning electron microscope (SEM) analysis to provide actionable failure analysis results in hours rather than days (Fig. 1).

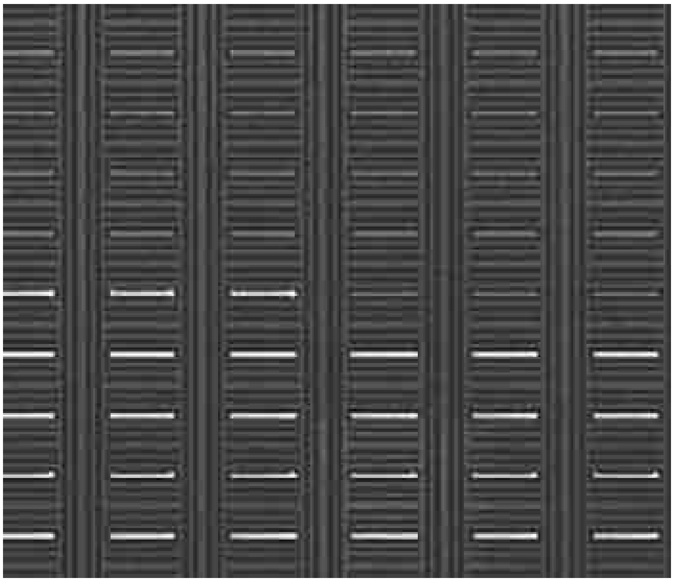


1. Short-flow test methodology combines in-fab electrical testing of specially designed short-flow test wafers with FIB/SEM analysis to provide actionable failure analysis in hours rather than days or weeks.

METHODOLOGY

Test wafers, known as characterization vehicles (CVs), contain test structures specifically designed to be sensitive to design-process interactions that impact product yields. The CVs contain structures customized for specific processes or process modules. CVs cover most front-end-of-line (FEOL) and back-end-of-line (BEOL) issues, and can provide comprehensive coverage of systematic and random defect mechanisms with statistical sensitivity in the 1-3 ppb failure range using only three to six wafers. Moreover, because the CVs are short-flow test chips designed to be manufactured in days (compared with months in the case of full-flow product wafers), substantially faster learning cycles can be realized.

The dedicated, massively parallel tester is specifically designed for use with the CVs in the cleanroom, and is 10-15 times faster than current generation parametric testers. Electrical test data is automatically sent to a comprehensive analysis software, which provides detailed characterization of the process defectivity modes. The program correlates electrical data with any available visual defect data, and allows the operator to select and categorize defects based on a wide variety of attributes. The program exports selected defect data and locations through a file-based interface.

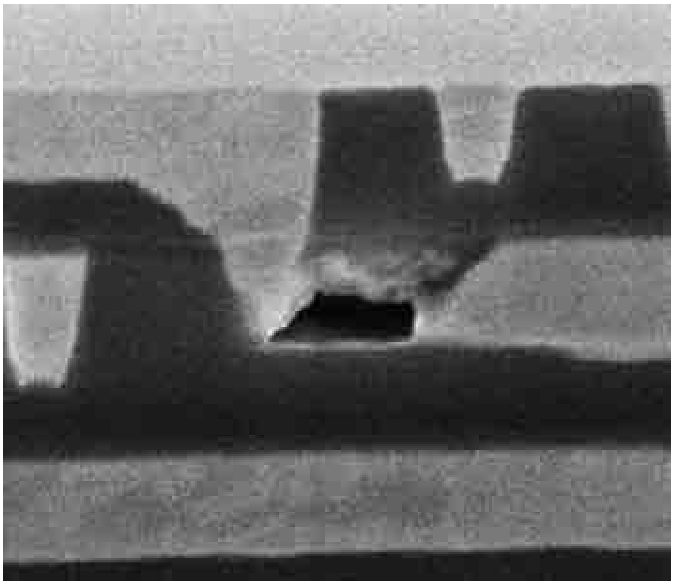


2. The location of the break in this long chain via structure is easy to see with voltage contrast imaging. The change in surface potential affects the strength of the secondary electron signal from which the image is formed, permitting the operator to quickly find and mark the exact location of selected defects.

When electrical testing is complete, the wafer and device under test (DUT) location data that contains the defect are transferred to an inline, full-wafer dual-beam FIB/SEM for detailed characterization of selected defects. Dual-beam defect analysis uses the FIB to cut cross-sections through selected defects, revealing subsurface structure for high-resolution imaging with the SEM. The ion and electron beams are configured so that the SEM can image the FIB cross-section after it is milled. The automated high-speed stage quickly and accurately positions defects for cross-sectioning and imaging based on the data received from the electrical tester.

The analysis proceeds in two phases. In the first phase, the operator uses voltage contrast imaging to identify and refine failure locations. Voltage contrast occurs in an SEM image as a result of electrical potential differences at the sample surface. Charge deposited by the scanning electron or ion beam accumulates on non-conductive surfaces or on conductive elements that are not grounded. The accumulated charge alters the surface potential and the strength of the secondary electron signal used to form SEM images. Voltage contrast provides a very fast way to find shorts and opens in microelectronic circuits. Once a defect is located, the dual-beam FIB/SEM automatically mills a fiducial marker with the FIB. In this work, we localized open defects (>100 M-Ω) and shorts (<50 K-Ω) at a maximum rate of about ten sites per hour. Defect sizes ranged down to 50 nm to as large as 40,000 µm2.

In the second phase of the analysis, the dual-beam FIB/SEM automatically revisits each marked defect. Using feature recognition routines, it locates the previously placed fiducial marks and mills a precisely placed cross-section through the defect, then acquires a high-resolution image of the subsurface structure. The system may also alternatively use a slice-and-view methodology where a small amount of the wafer surface is milled in incremental steps and then imaged after each step. The cross-sectioning and imaging operation takes about seven minutes per site. The defect analyzer uploads the images to the analysis database in the electrical tester where they are linked to the specific defect. The images can be used along with all other attributes stored in the database to prioritize corrective action and drive yield improvement.

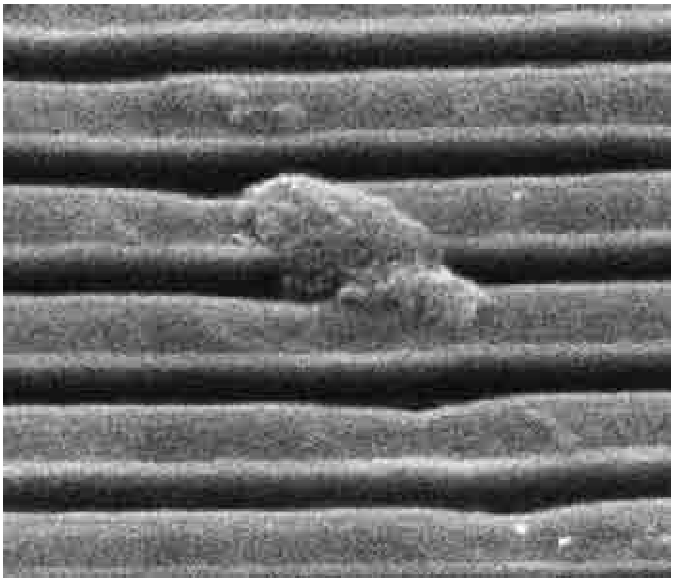


3. The defect localized in Figure 2 is shown again here after cross-sectioning. The dual-beam FIB/SEM automatically relocates each marked defect, cuts a cross-section and acquires images. The cross-sectioning and imaging operation takes about seven minutes per site, depending on the number and resolution of the images.

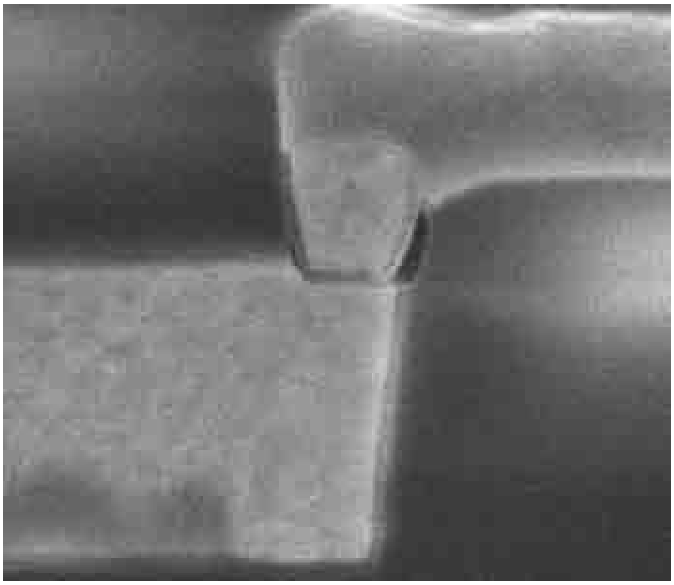
BEOL MODULE RESULTS

The BEOL characterization used a three-layer metal CV test chip from Metal 1 through Metal 3, including vias. The design of the CV included over 1300 product layout variations typical of system-on-a-chip (SoC) products. For example, to characterize the response to via pitch the test chip includes a range of structures with varied pitches and coverage in different top and bottom metal. Another set of structures looks for the influence of metal topography on upper layer metal shorts. The range and distribution of structure parameters are rigorously designed to support statistically significant conclusions in the ppb failure range required for advanced processes while using the minimum number of test wafers.

After completing the short-flow process and typical inline inspection, the BEOL CV was tested in the dedicated electrical tester. Electrical testing took approximately three hours per 300 mm wafer for all die and structures. The electrical test data were analyzed by the analysis software to determine characterization, including failure rates, yields and spatial patterns for each structure type in the analysis software. This permits the development of correlations between defectivity and layout attributes, or any other available inspection data. For instance, Metal 3 shorts caused by underlying metal topography can be analyzed to identify the densities, linewidths and line spaces associated with the greatest defectivity.



4. This metal short was located with voltage contrast imaging. The dual-beam FIB/SEM can immediately cross-section the defect.



5. This open contact was located with voltage contrast imaging. Foreign residue is the suspected cause.

The analysis software can also select only defects that were not detected by other inline inspection — non-visual defects. Selected sites can then be exported to the defect analyzer for further characterization. Figure 2 shows a voltage contrast image of one of the defects selected in Figure 1. Figure 3 shows an SEM image of the FIB cross-section of the same defect. A metal void in the lower link of the chain is readily apparent.

The short-flow method can detect shorts as well as opens. Generally, opens are located more quickly (<2 min/site) than shorts (<15 min/site). Figure 4 shows a metal short that was isolated using voltage contrast and FIB techniques.

The poly module CV characterizes shallow trench isolation (STI), polysilicon and silicide modules. It includes a variety of designed experiments with polysilicon structures over both field and active regions, and can provide both functional and parametric characterization. Cross-sectioning and imaging in the dual-beam FIB/SEM can then help to determine the root cause of the defect.

The FEOL CV performs extensive characterization of contacts; in this case, metal contacts to local interconnect. Figure 5 shows an FIB cross-section of an open contact. A foreign residue layer was suspected as the cause. Although the electrical discontinuity is not as obvious in this cross-sectional image, the voltage contrast imaging used to locate the defect provides hard evidence that the contact is open.

The fraction of defects that cannot be detected by conventional inspection techniques has increased with each decreasing technology node. Conventional methods of detecting these non-visual defects cannot be applied until wafer processing is nearly complete. The delay detecting and analyzing these non-visual defects lengthens process development and yield learning cycles, slows ramps to volume production, and puts substantial work-in-progress at risk in high-volume manufacturing.

The technique described, combined with automated FIB/SEM defect analysis, can provide an order-of-magnitude reduction in non-visual defect detection and analysis times. The rigorously designed test structures provide excellent sensitivity across a range of design parameters, with samples sizes sufficient to support statistically significant assessments at the level of a few defects per billion. The technique combines reliable detection of killer defects with excellent discrimination against nuisance defects. All of these benefits contribute significantly to shorter product and process development cycles, faster ramps to profitable volume, and faster recovery from yield excursions.

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WHO SETS THE RULES FOR ELECTRICAL TESTING AND SAFETY?

Fluke Corporation

ALPHABET SOUP

There is no question that electrical safety is a key concern for electricians and engineers, their employers, unions and the government.

Every day, an average of 9,000 workers in the U.S. suffer disabling injuries on the job. Insurance industry estimates put the direct cost of workplace injuries at more than $40 billion. With costs that high, no wonder so many government agencies and private groups hold pieces of the safety puzzle.

To maximize safety for yourself and your team, you need a solid understanding of the rules and standards that govern safe electrical work. This article will help you cut through the alphabet soup of safety organization names to see how each plays a role in safety.

We'll check them out in two groups. First, we'll look at the government agencies that oversee workplace safety, such as the U.S. Occupational Safety and Health Administration (OSHA) and the National Institute for Occupational Safety and Health (NIOSH).

Then we'll examine the independent safety and standards organizations, including the National Fire Protection Association (NFPA), the American National Standards Institute (ANSI), the Institute of Electrical and Electronics Engineers (IEEE) and the International Electro- Technical Commission (IEC). Though they're not part of government, they too help set the rules of the safety game.

THE GOVERNMENT AGENCIES

First, where did OSHA and NIOSH come from, and what do they do?

Both agencies were created by the federal Occupational Safety and Health Act of 1970. OSHA is in the U.S. Department of Labor and is responsible for developing and enforcing workplace safety and health regulations. In addition, many states have their own occupational safety agencies that work with OSHA and govern workplace safety on the state level.

NIOSH is an agency of the U.S. Department of Health and Human Services, established to help assure safe and healthful working conditions by providing research, information, education, and training in the field of occupational safety and health.

In other words, OSHA sets and enforces the rules, while NIOSH provides helpful information on workplace safety. Here are some examples:

Several OSHA regulations have an impact on electrical workplace safety. For instance:

- 29 CFR (Code of Federal Regulations) 1910 Subpart I sets standards for Personal Protective Equipment (PPE), including eye and face protection, footwear and protection for electrical workers, such as insulating blankets, gloves and sleeves.
- The key electrical safety rules are part of 29 CFR 1910 Subpart S, including design safety standards for electrical systems, safe work practices, maintenance requirements and safety requirements for special equipment. This regulation also covers

training requirements, sets guidelines for work on energized parts, outlines lockout/tagout procedures and provides rules for use of PPE in electrical work. The OSHA website provides other electrical safety resources.

While OSHA sets the broad safety agenda, it leaves some details to others. For example, the OSHA electrical safety rules in 1910 Subpart S specifically refer the reader to NFPA and ANSI codes and standards for help in complying with OSHA. These include NFPA 70E (Standard for Electrical Safety in the Workplace), ANSI/NFPA 70 (National Electrical Code) and others.

Here's an example of how the standards work together. OSHA's safety-related work practice standards in Subpart S do not currently address flame-resistant (FR) clothing. However, OSHA standard 29 CFR 1910.335 (a)(2)(ii) requires use of protective shields, protective barriers, or insulating materials to protect employees from shock, burns or other electrically related injuries while working near exposed energized parts or where dangerous electric heating or arcing might occur. Chapter 1 of NFPA 70E-2004 contains specific requirements and methodology for hazard assessment and selection of protective clothing and other personal protective equipment (PPE). Employers may follow NFPA 70E flash-hazard requirements as a way of meeting the OSHA standard.

THE KEY DISTINCTION IS THIS:

OSHA 1910 Subpart S and other OSHA safety and health standards are law. Failure to follow these standards could result in a citation, a work shutdown, fines or other sanctions. The NFPA, ANSI and other standards OSHA refers to, on the other hand, are intended as guidelines to safety.

"We're pointing employers and employees to these documents as sources for additional information," said David Wallis, director of the OSHA office of engineering safety. "For safe work practices there are some general type requirements in OSHA 1910 related to protection from electric shock and electric arc hazard. Employers can look toward NFPA 70E for more specific information about the kind of equipment they need to protect their employees."

"There is another caveat I might explain," Wallis continued. "Sometimes OSHA will have a specific requirement not contained in NFPA 70E, or where the 70E provision might not be quite as stringent. In that case, OSHA would expect employers to comply with the OSHA standard. Compliance with NFPA 70E would not automatically be considered adequate."

NIOSH: HELPFUL INFORMATION

While OSHA sets the rules, and sometimes levels penalties, NIOSH provides useful safety information. A good example is a new 88-page electrical safety handbook, Electrical Safety - Safety and Health for Electrical Trades Student Manual, available for downloading in portable document format. The NIOSH website also provides a number of electrical safety alerts, reports and links to other electrical safety resources.

NFPA ESTABLISHES STANDARDS THROUGH CONSENSUS

Outside government, a key player in establishing electrical safety practices is the nonprofit National Fire Protection Association. The NFPA sets and updates more than 300 safety codes and standards, covering everything from building construction to connectors for fire hose. NFPA standards are set through consensus, developed by more than 200 committees of volunteers from industry, unions and other interest groups.

For electrical workplace safety, the key NFPA standard is NFPA 70E, Standard for Electrical Safety in the Workplace. The 2004 edition was issued by the NFPA Standards Council and approved as an American National Standard in February 2004. NFPA 70E is written to correlate with the National Electrical Code (NEC), which many jurisdictions adopt as part of local building codes and regulations. But NFPA 70E focuses on such issues as safety-related work practices, maintenance of safety equipment, safety requirements for special equipment and safety-related installation requirements. It is intended for use by employers, employees, and OSHA.

NFPA 70E uses six categories of hazard and risk for electrical work, from minus one up to four. As the work environment and the type of job become more hazardous, the need for protection increases. The standard also makes it clear that test equipment Ñ rated and designed for the circuits and environments where it will be used, and inspected before each shift Ñ is an integral part of the PPE electrical workers must use on the job.

The NFPA 70E standard provides extensive information on what it takes to work safely, and to run an effective electrical safety program. It provides guidance on employee training, work planning and procedures (including lockout/tagout) and use of PPE. Whether you're a professional electrician, an apprentice or a supervisor, NFPA 70E is must reading. And don't forget, OSHA also refers to NFPA 70E.

ANSI SETS STANDARDS FOR EQUIPMENT

The American National Standards Institute (ANSI) also plays a role in electrical safety. This private, non-profit organization administers and coordinates the U.S. voluntary standardization and conformity assessment system. And it represents the U.S. in international standards organizations, such as the International Organization for Standardization (ISO) and the

IEC.

OSHA electrical safety regulation 1910 Subpart S refers to several ANSI standards. The key ANSI standards involving electrical safety are ANSI C33.27-74 (Safety Standard for Outlet Boxes and Fittings for Use in Hazardous Locations) and ANSI S82.02 (see below), which provides important safety rules for electrical test instruments. ANSI C2-81 (National Electrical Safety Code) deals with electric installations of more than 1000 volts, an area beyond the scope of this article.

IEEE HELPS CALCULATE ARC FLASH HAZARD

Another authority in safety is the Institute of Electrical and Electronics Engineers. IEEE 1584ª- 2002, Guide for Arc Flash Hazard Calculations, does just what its title suggests, providing technical information employers can use to determine the arc flash hazards present in the workplace. IEEE publishes a number of other useful safety standards and practice guides, including the twelvevolume IEEE Color Booksª series.

KEY SAFETY RULES FROM INTERNATIONAL PARTNERS

To make electrical measurements safely, it pays to stretch your horizons. Some of the most important safety guidelines for electrical measurement have been developed in cooperation with the International Electrotechnical Commission (IEC), the leading global organization that prepares and publishes international standards for all electrical and related technologies.

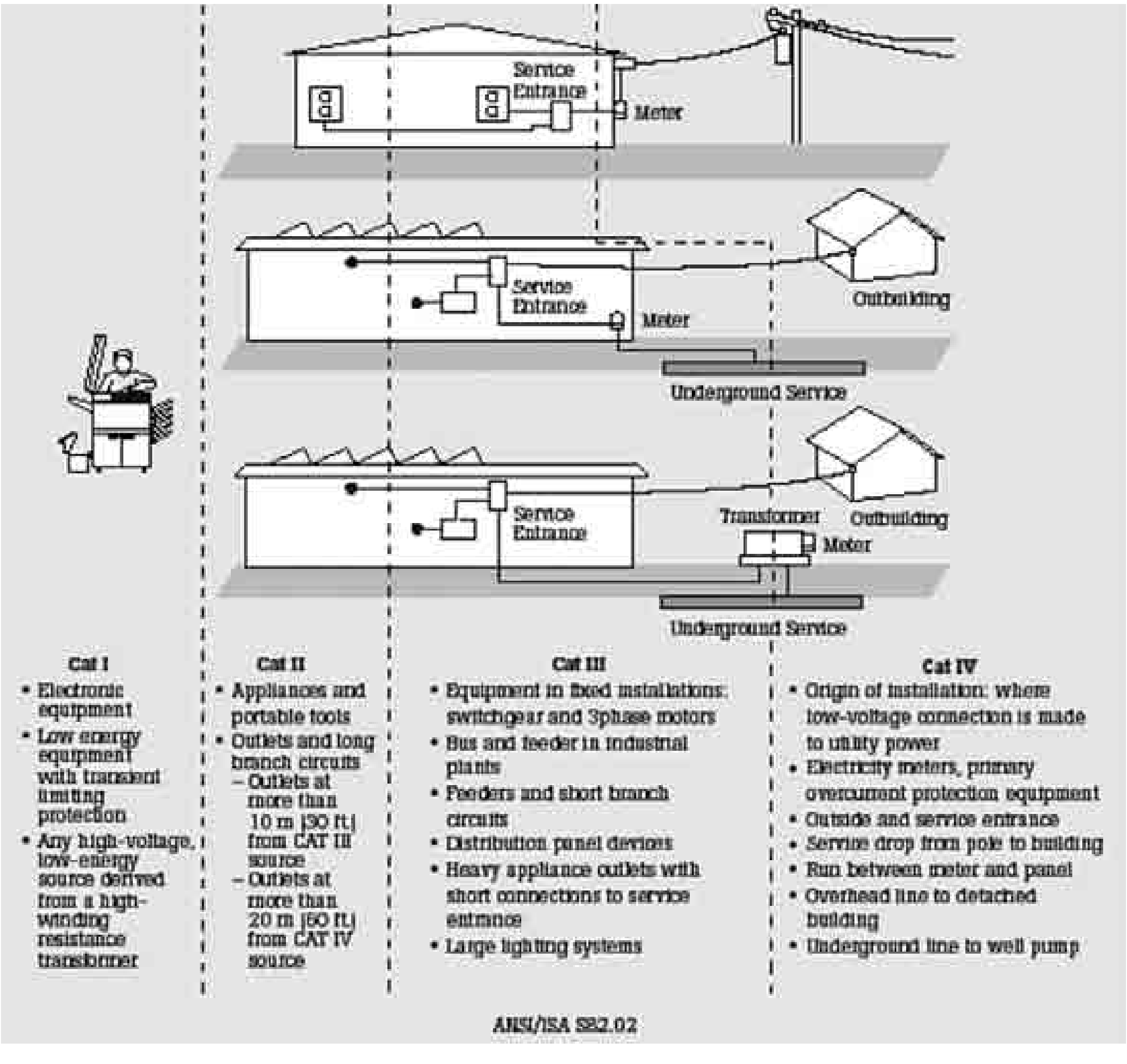
ANSI, the Canadian Standards Association (CSA), and the IEC have created more stringent standards for voltage test equipment used in environments of up to 1000 volts. The pertinent standards include ANSI S82.02, CSA 22.2-1010.1 and IEC 61010. These standards cover systems of 1000 volts or less, including 480-volt and 600-volt, three-phase circuits. For the first time, these standards differentiate the transient hazard by location and potential for harm, as well as the voltage level.

In addition, the 2000 edition of IEC 61010 requires that multimeters and similar equipment shall not cause a shock, fire, arcing or explosion hazard even if subjected to operator error (for instance, connecting the meter to an energized circuit when set to the ohms position). Fluke meters not only protect the user in such circumstances Ñ they also protect themselves, and keep working. ANSI and CSA are now in the process of adopting these more stringent IEC standards.

These standards establish an important four-category system for rating the electrical hazards electricians face when taking measurements on so-called "low voltage" equipment Ñ up to 1000 volts.

ANSI, CSA and IEC define four measurement categories of over-voltage transient impulses (voltage spikes). The rule of thumb is that the closer the technician is working to the power source, the greater the danger and the higher the measurement category number. Lower category installations usually have greater impedance, which dampens transients and helps limit the fault current that can feed an arc.

• CAT (Category) IV is associated with the origin of installation. This refers to power lines at the utility connection,


Service
Entrance
Meter
Service
Entrance
Meter
Outbuilding
Underground Service
Service
Entrance
Transformer
Outbuilding
Meter
Underground Service
Cat I
• Electronic equipment
• Low energy equipment with transient limiting protection
• Any high-voltage, low-energy source derived from a high-winding resistance transformer
Cat II
• Appliances and portable tools
• Outlets and long branch circuits
– Outlets at more than 10 m (30 ft) from CAT III source
– Outlets at more than 20 m (60 ft) from CAT IV source
Cat III
• Equipment in fixed installations: switchgear and 3phase motors
• Bus and feeder in industrial plants
• Feeders and short branch circuits
• Distribution panel devices
• Heavy appliance outlets with short connections to service entrance
• Large lighting systems
Cat IV
• Origin of installation: where low-voltage connection is made to utility power
• Electricity meters, primary overcurrent protection equipment
• Outside and service entrance
• Service drop from pole to building
• Run between meter and panel
• Overhead line to detached building
• Underground line to well pump
ANSI/ISA S82.02

as well as the service entrance. It also includes outside overhead and underground cable runs, since both may be affected by lightning.

- CAT III covers distribution level wiring. This includes 480-volt and 600-volt circuits such as 3-phase bus and feeder circuits, motor control centers, load centers and distribution panels. Permanently installed loads are also classed as CAT III. CAT III includes large loads that can generate their own transients. At this level, the trend to using higher voltage levels in modern buildings has changed the picture and increased the potential hazards.
- CAT II covers the receptacle circuit level and plug-in loads.
- CAT I refers to protected electronic circuits.

Some installed equipment may include multiple categories. A motor drive panel, for example, may be CAT III on the 480-volt power side, and CAT I on the control side.

A higher CAT number refers to an electrical environment with higher power available and higher-energy transients. This is a key principle to understand when it comes to choosing and using test instruments. A multimeter designed to a CAT III standard can resist much higher-energy transients than one designed to CAT II standards. Within a category, a higher voltage rating denotes a higher transient withstand rating; e.g., a CAT III-1000 V meter has superior protection compared to a CAT III-600 V rated meter.

TRANSIENT PROTECTION

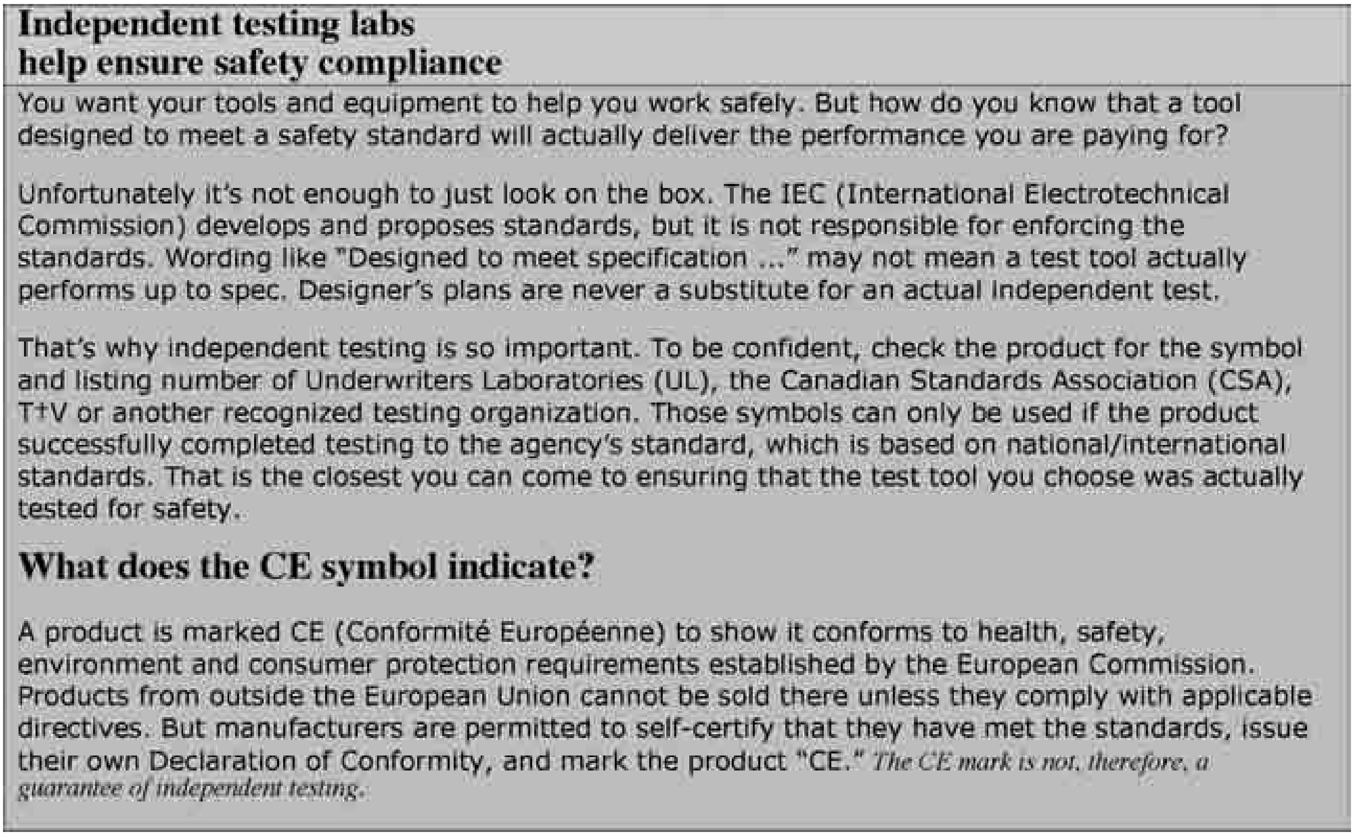
The real issue for meter circuit protection is not just the maximum steady state voltage range, but a combination of both steady state and transient overvoltage withstand capability. Transient protection is vital. When transients ride on high energy circuits, they tend to be more dangerous because these circuits can deliver large currents.

If a transient causes an arcover, the high current can sustain the arc, producing a plasma breakdown or explosion, which occurs when the surrounding air becomes ionized and conductive. The result is an arc blast, a disastrous event which causes numerous injuries every year.

The concept of categories is not new and exotic. It is simply an extension of the same common-sense concepts that people who work with electricity professionally use every day. It's another tool you can use to better understand the hazards you face on the job, and work safely.

All of the regulations we have covered are built in the same way. They grow from experience, and they are based on experience and sound, common-sense principles. No tool, however, can do the job alone. It's up to you, the user, to learn these safety regulations and standards, and use them effectively on the job.

After all, it's your safety at stake. Read up, and work safely.



Independent testing labs help ensure safety compliance

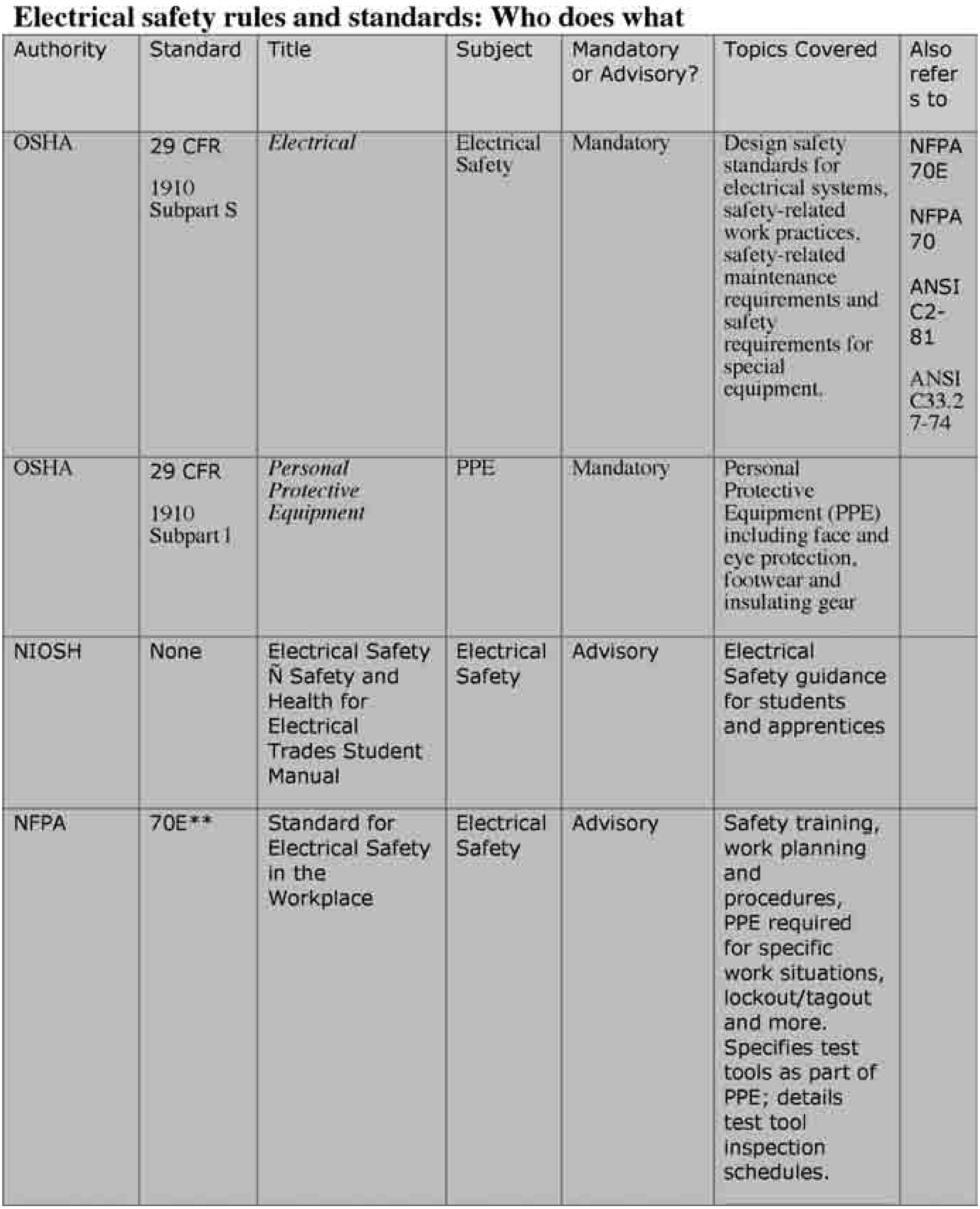
You want your tools and equipment to help you work safely. But how do you know that a tool designed to meet a safety standard will actually deliver the performance you are paying for?

Unfortunately it's not enough to just look on the box. The IEC (International Electrotechnical Commission) develops and proposes standards, but it is not responsible for enforcing the standards. Wording like "Designed to meet specification ..." may not mean a test tool actually performs up to spec. Designer's plans are never a substitute for an actual independent test.

That's why independent testing is so important. To be confident, check the product for the symbol and listing number of Underwriters Laboratories (UL), the Canadian Standards Association (CSA), T†V or another recognized testing organization. Those symbols can only be used if the product successfully completed testing to the agency's standard, which is based on national/international standards. That is the closest you can come to ensuring that the test tool you choose was actually tested for safety.

What does the CE symbol indicate?

A product is marked CE (Conformité Européenne) to show it conforms to health, safety, environment and consumer protection requirements established by the European Commission. Products from outside the European Union cannot be sold there unless they comply with applicable directives. But manufacturers are permitted to self-certify that they have met the standards, issue their own Declaration of Conformity, and mark the product "CE." *The CE mark is not, therefore, a guarantee of independent testing.*



Electrical safety rules and standards: Who does what

Authority	Standard	Title	Subject	Mandatory or Advisory?	Topics Covered	Also refers to
OSHA	29 CFR 1910 Subpart S	*Electrical*	Electrical Safety	Mandatory	Design safety standards for electrical systems, safety-related work practices, safety-related maintenance requirements and safety requirements for special equipment.	NFPA 70E NFPA 70 ANSI C2-81 ANSI C33.27-74
OSHA	29 CFR 1910 Subpart I	*Personal Protective Equipment*	PPE	Mandatory	Personal Protective Equipment (PPE) including face and eye protection, footwear and insulating gear	
NIOSH	None	Electrical Safety Ñ Safety and Health for Electrical Trades Student Manual	Electrical Safety	Advisory	Electrical Safety guidance for students and apprentices	
NFPA	70E**	Standard for Electrical Safety in the Workplace	Electrical Safety	Advisory	Safety training, work planning and procedures, PPE required for specific work situations, lockout/tagout and more. Specifies test tools as part of PPE; details test tool inspection schedules.	

NFPA	70**	National Electrical Code	Electrical Safety	Mandatory*	Electrical installations in buildings, generally operating at 600 volts or less	
ANSI/IEEE	C2-81**	National Electrical Safety Code	Electrical Safety	Mandatory*	Governs electric utility and heavy industrial installations, often operating in thousands of volts	
ANSI	S82.02	Safety requirements for electrical equipment for measurement, control, and laboratory use	Test tool safety	Advisory	Hand-held probe assemblies and hand-held current clamps for electrical measurement and test. Establishes four categories of overvoltage transient hazard	
CSA	22.2-1010.1					
IEC	61010					
IEEE	1584™-2002	Guide for Arc Flash Hazard Calculations	Arc Flash	Advisory	Determination of arc flash hazard	
IEEE	Color Books	12 titles in series	Multiple	Advisory	Safety and other recommended practices for electrical work and electrical installations	

* Adopted both directly and indirectly in many U.S. and international jurisdictions. ANSI/IEEE C2 is typically adopted by state or local public utility commissions.

COMPARATIVE CORROSION AND CURRENT BURST TESTING OF COPPER AND ALUMINUM ELECTRICAL POWER CONNECTORS

Ron Frank, Eng., Member, IEEE, Canadian Copper and Brass Association and Chris Morton, P.Eng., Member, IEEE, Powertech Labs Inc.

Abstract — Crimped and mechanically bolted aluminum and copper connectors are commonly used for terminating industrial electrical power cables with ratings up to 600 V. Aluminum connectors are available for use with aluminum or copper conductor, and copper connectors are available for use with copper conductor only.

The performance of copper and aluminum connectors was compared by conducting accelerated aging under corrosive environmental conditions. The testing consisted of 2,000 hours of cyclic salt fog environmental exposure, in conjunction with periodic electrical current burst testing. The connectors were evaluated by comparing the change in resistance of the test samples as the test progressed.

I. INTRODUCTION

For industrial and commercial applications, crimped and mechanically bolted aluminum and copper connectors are commonly used for terminating power cables. Copper connectors are available for use with copper conductor, and aluminum connectors are available for use with copper and aluminum conductor. Test standards for power connectors include CSA C57 and ANSI C119.4 500-cycle current cycling tests, which are intended to establish long-term performance.

There are significant differences in the material and electrical properties of aluminum and copper and their oxides, which may affect their long-term performance.

Aluminum oxidizes readily when exposed to air, and a strongly attached, hard outer layer of electrically insulating oxide quickly forms around the metal. For this reason, aluminum connectors are usually manufactured with a tin coating which is intended to prevent surface oxidation of the connector from occurring. Aluminum crimp connectors are also pre-filled with oxide inhibiting compound to reduce oxidation between the conductor and connector when in service. Aluminum conductors must always be wire brushed to remove the oxide layer, and oxide-inhibiting compound is immediately applied to reduce oxidation.

Copper also oxidizes when exposed to air, but the oxide that forms is relatively soft and conductive, although not as conductive as the base metal. For this reason, copper connectors can often be installed without oxide inhibitor. Wire brushing of the conductor, although recommended, is not as critical as with aluminum. Copper connectors are often manufactured with a tin coating to reduce surface oxidation and discolouration, but they are also available without tin coating.

When copper and aluminum are brought into direct contact in the presence of moisture, a strong galvanic reaction takes place due to the dissimilar properties of the metals. For this reason, aluminum connectors are not used with copper conductor unless an interface material that is more compatible with both copper and aluminum is present, such as tin.

However, tin is also susceptible to oxidation, and if the tin layer is compromised, then galvanic corrosion between the base metals can still occur.

The differences in properties of copper and aluminum may result in a significant performance difference in the various types of electrical connectors when in long-term service.

II. OBJECTIVE

The objective of this study was to compare the contact resistance at the junction between the connector and conductor under harsh environmental laboratory testing conditions for the following material combinations:

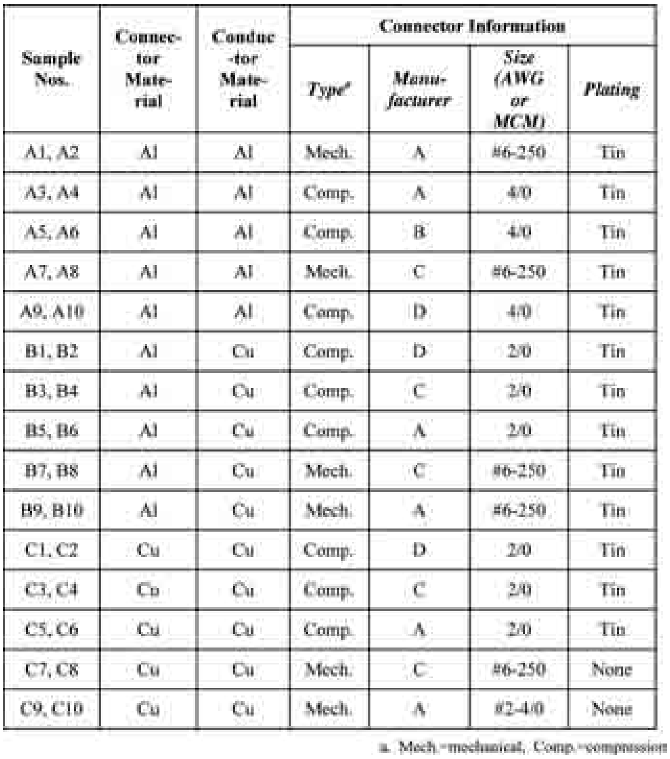
- copper connectors on copper conductor,
- aluminum connectors on copper conductor, and
- aluminum connectors on aluminum conductor.

The connectors, conductor, and oxide inhibitor used to make the samples were standard commercially available varieties obtained from several different manufacturers.

Manufacturer names are omitted from this paper since the intention of the study was not to compare specific manufacturers' products. A variety of commonly available products were used so that general conclusions could be drawn.

III. TEST SAMPLES

The test samples used in the study were combinations of copper and aluminum conductors and connectors, with all components being standard off-the-shelf varieties. Copper conductor was bare 19-strand 2/0 AWG, and aluminum conductor was 18-strand compact 4/0 AWG. Conductor sizes were selected to be approximately the same ampacity. Connectors were a combination of compression and mechanical bolted type 1-hole lug connectors, with a total of ten connectors of each material combination used. All aluminum compression connectors were tin plated and supplied pre-filled with oxide inhibitor. A list of the test samples is provided in Table I, and a photograph of the samples as received is shown in Fig. 1.



Sample Nos.	Connec-tor Mate-rial	Conduc-tor Mate-rial	Connector Information			
			Type[a]	*Manu-facturer*	*Size (AWG or MCM)*	*Plating*
A1, A2	Al	Al	Mech.	A	#6-250	Tin
A3, A4	Al	Al	Comp.	A	4/0	Tin
A5, A6	Al	Al	Comp.	B	4/0	Tin
A7, A8	Al	Al	Mech.	C	#6-250	Tin
A9, A10	Al	Al	Comp.	D	4/0	Tin
B1, B2	Al	Cu	Comp.	D	2/0	Tin
B3, B4	Al	Cu	Comp.	C	2/0	Tin
B5, B6	Al	Cu	Comp.	A	2/0	Tin
B7, B8	Al	Cu	Mech.	C	#6-250	Tin
B9, B10	Al	Cu	Mech.	A	#6-250	Tin
C1, C2	Cu	Cu	Comp.	D	2/0	Tin
C3, C4	Cu	Cu	Comp.	C	2/0	Tin
C5, C6	Cu	Cu	Comp.	A	2/0	Tin
C7, C8	Cu	Cu	Mech.	C	#6-250	None
C9, C10	Cu	Cu	Mech.	A	#2-4/0	None

a. Mech.=mechanical, Comp.=compression

TABLE I. CONNECTOR SAMPLES USED FOR THE TESTING

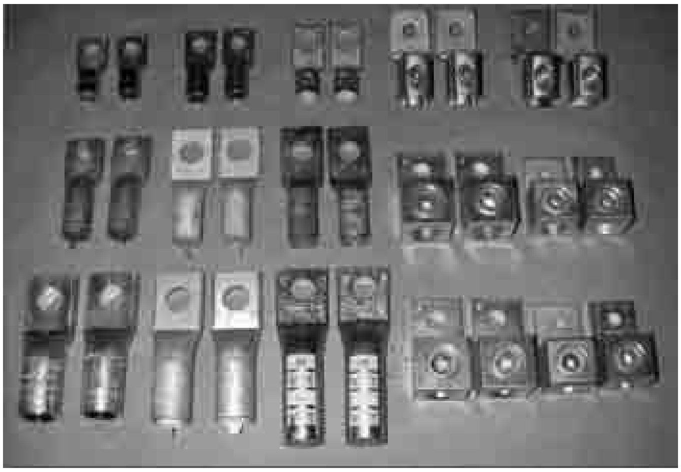


Figure 1. Connector samples used for corrosion and current burst testing

A. CONNECTOR INSTALLATION PROCEDURES

Connectors were installed according to the manufacturer's recommendations. This included wire brushing the conductor, applying an off-the-shelf oxide inhibitor (for aluminum mechanical connectors only), and crimping of the compression connectors using a standard manual crimping tool. No oxide inhibitor was applied to any of the copper-to-copper connections. Mechanical connectors were installed using torque levels appropriate to the screw size in the clamping mechanism of the connector.

B. CONNECTOR SAMPLE ASSEMBLIES

Each connector sample was installed on approximately 0.5 m of conductor, with a current equalizer on the end of the conductor opposite each connector. The equalizer was intended to provide a solid electrical connection to each strand of the conductor, so that current could be applied uniformly to the conductor. Welded aluminum equalizers were used on the aluminum conductor, and brazed copper equalizers were used on the copper conductor. Three groups of 10 samples each were connected together back-to-back to form three series circuits, which were labeled as sample sets 'A' (all aluminum), 'B' (copper conductor with aluminum connectors), and 'C' (all copper). A photograph of a complete connector assembly, with 10 connectors and equalizers, is shown in Fig. 2. Control conductors were subjected to the corrosion and current burst testing along with the connector and conductor samples. These consisted of 1 m lengths of copper and aluminum bare conductor with no connector attached.

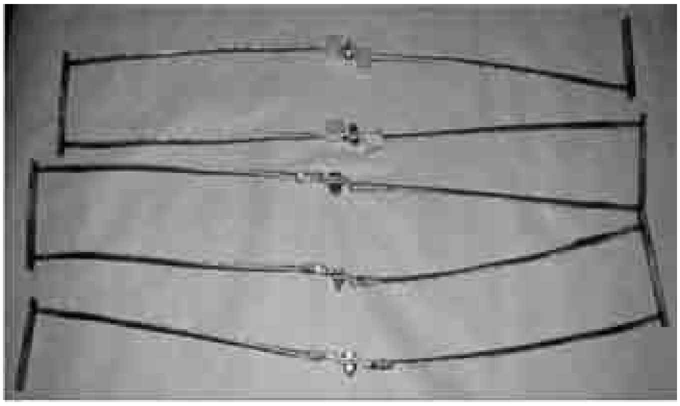


Figure 2. Connector sample assembly with equalizers and conductor (copper conductor with aluminum connector samples shown).

IV. TEST PROCEDURES

The testing consisted of periods of corrosive environmental exposure, followed by application of high current. This was intended to produce conditions in which connectors that were susceptible to corrosion showed an increase in contact resistance as the testing progressed.

The cyclic testing was conducted in the following sequence:

- Salt fog corrosion cycling was carried out for 500 hour blocks of time.
- Current burst tests were carried out following each 500 hour salt fog period.
- DC resistance readings of each connector were made approximately every 170 hours during the corrosion testing, and before and after each set of current burst tests.
- A total of four sets of salt fog and current burst tests were conducted, for a total of approximately 2,000 hours of salt fog testing.

A. CORROSION CYCLING

Connector sample groups were arranged on a three-tier PVC rack in an environmental chamber with the conductors and connectors oriented horizontally, and the connectors suspended in clear air. The positions of the connector sets were exchanged periodically so that consistent environmental exposure from sample to sample was achieved over the testing period.

Each 4 hour corrosion testing cycle consisted of the following steps:

- Salt fog spray for a period of 1 hour 45 minutes, consisting of a fine mist of aerated 3% NaCl solution buffered to a pH of 5.5 using nitric acid.

- Dry heat for a period of 2 hours, reaching a maximum of 70°C during the 2 hour period.
- Clear water rinse for a period of 15 minutes.

B. CURRENT BURST TESTING

The reason for conducting current burst testing was to encourage accelerated degradation at the connector contact with the conductor. For the test, current levels of 1750 Arms for 4/0 aluminum conductor, and 1800 Arms for 2/0 copper conductor were determined to be sufficient to produce the desired effect. For each test, the current was held at the required level long enough to raise the temperature of the control conductor to 250°C, as determined by a thermocouple measurement at the center of the control conductor span.

Typically, this required an application of current for approximately 50 seconds, starting with a conductor at near room temperature. The calculation to determine these levels is described in detail in Appendix A.

Samples were subjected to current burst testing as follows:

- Each set of 10 connectors, which were joined together in series, were subjected to current burst testing simultaneously.
- The control conductor was placed in series with the connector assembly. A thermocouple was attached to the center of the length of each control conductor to measure the conductor temperature during current burst testing.
- Five short duration bursts of high current were applied in succession. The control sample was allowed to cool to 40°C or less between each current burst.

The contact resistance of each connector was measured at room temperature using a micro-ohmmeter before and after each set of five current burst tests.

C. DC RESISTANCE MEASUREMENTS

All contact resistances were measured on dry samples at room temperature (20°C) using a LEM model D3700 microohmmeter.

Since resistances were all measured at the same temperature level, no correction was applied.

Resistances were measured from the equalizer to the body of the connector, so that an average reading was obtained for each connector. Four point resistance measurements were made to eliminate lead resistance errors, and measurements were made at a current level of 10 A DC.

V. TEST RESULTS

A. RESISTANCE MEASUREMENTS

1) Raw Test Data: Bar charts showing all of the measured resistances during the testing are shown in Fig. 3 through Fig. 5. The resistance values are displayed in chronological order from left to right, so that the left-most bar is the reading before testing, and the right-most bar is the reading after 2000 hours of environmental exposure and final current burst testing.

2) Aluminum Equalizer Failure and Corrected Results:

During the last set of current burst tests (after 2000 hours of corrosion cycling), a problem with the welded aluminum equalizers became apparent when one of the equalizers, on sample no. A7, was damaged by excessive heating during the first current shot. It appeared that some of the welded aluminum equalizers were being excessively degraded by the environmental exposure.

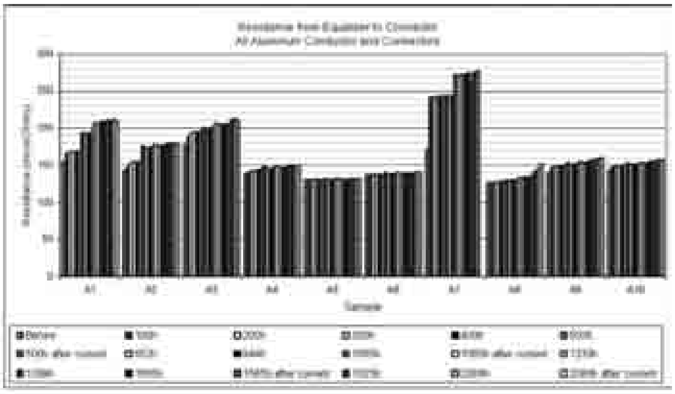


Figure 3. Resistance measurements for all-aluminum connections (Group A).

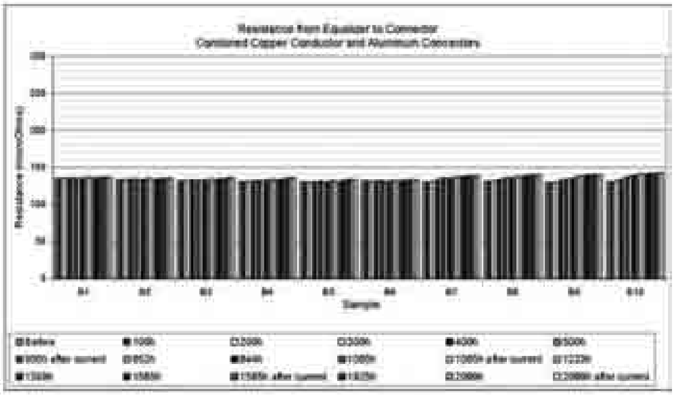


Figure 4. Resistance measurements for aluminum connectors on copper conductor (Group B).

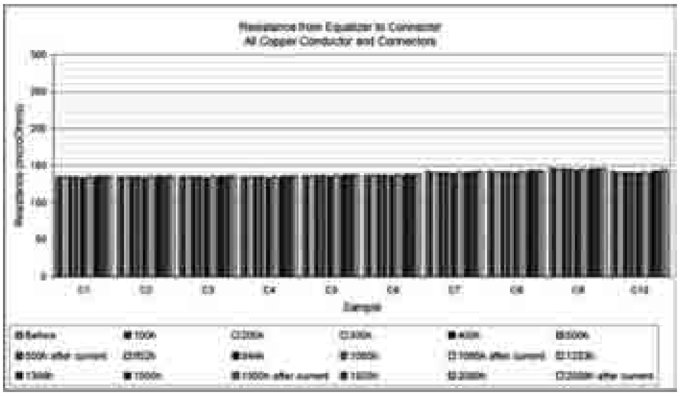


Figure 5. Resistance measurements for all-copper connections (Group C).

A current distribution measurement was necessary to confirm which equalizers had probably sustained damage. The current distribution was determined by measuring the voltage drop over a fixed distance on each of the 11 outer strands with a fixed DC current of 10 A applied to the entire conductor from equalizer to connector. The equalizers with a small variation between voltage readings were assumed to have had an evenly distributed current, which indicated that the equalizer and connector were still making a consistent connection. The equalizer/connector groups with a large variation in voltage had either a poor connection at the equalizer, a poor connection at the connector, or both. A graph of the measured voltage values which have been normalized to the average reading for each equalizer is shown in Fig. 6. The results indicated that samples A1, A3, A7, A8, and A10 had a poor current distribution, and were suspected of being damaged. For these samples, the old equalizer was cut off, the conductor was thoroughly cleaned and wire brushed, and a new equalized connection was made using a new aluminum compression connector. The equalizer-to-connector resistances were then re-measured for these samples, and a small correction was made to compensate for the amount of conductor that was cut off. The new values were used as the final resistance readings.

A graph with the corrected measured resistances of the aluminum connectors with re-made equalizers is shown in Fig. 7. For the connectors with re-made equalizers, since the only valid readings were made at the beginning and end of the test, all other readings were omitted.

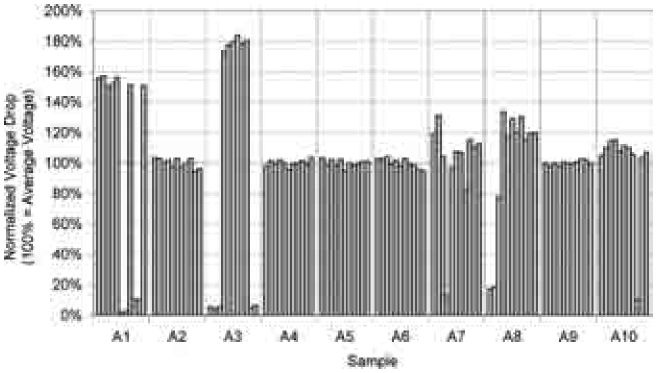


Figure 6. Current distribution measured by voltage drop along the conductor outer strands. Results were normalized to the average voltage for each equalizer.

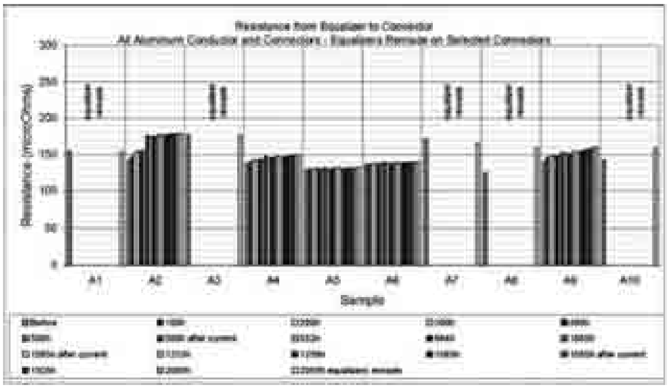


Figure 7. Corrected resistance measurements for all-aluminum connections (Group A).

B. CONNECTOR APPEARANCE

1) Aluminum Connectors: The aluminum connectors on both the aluminum and copper conductor showed a considerable amount of surface corrosion after testing, and a build-up of white oxidation. On some of the mechanical connectors, the tin plating had flaked off the surface and the underlying aluminum showed signs of corrosion. Photographs of the all-aluminum connectors before and after testing are shown in Fig. 8, and the aluminum connectors on copper conductor are shown in Fig. 9.

2) Copper Connectors: The copper connectors had a duller finish after the testing and showed some signs of surface oxidation, but the tin plating was intact (where present).

Photographs of the all-copper connections before and after testing are shown in Fig. 10.

VI. DISCUSSION

The measured resistance values are made up of a combination of the equalizer resistance, conductor resistance, and connector contact resistance. Since the conductor resistance dominates, even significant changes in the connector contact resistance may not result in a large change in the overall resistance reading. By calculating the resistance readings during the testing as a percentage of the initial resistance reading, the overall effect can be more easily seen.

Fig. 11 shows the percent change in resistance for all connectors, measured after each current burst test.

On average, the before-test equalizer-to-connector resistance readings were approximately 145uΩ for the aluminum conductor samples, and 135uΩ for the copper conductor samples. Initial contact resistance readings from the conductor to the connector were measured at approximately 10-15uΩ, or approximately 10% of the total resistance reading.

Assuming that most of the change in resistance during the test is due to an increase in connector contact resistance, then an increase in equalizer-to-connector resistance of 10% would correspond to an increase in connector contact resistance of over 100%. On this basis, an increase in the equalizer-to-connector resistance of 5% may be considered to be significant, and an increase of 10% or more may be considered to be a failure of the connector.

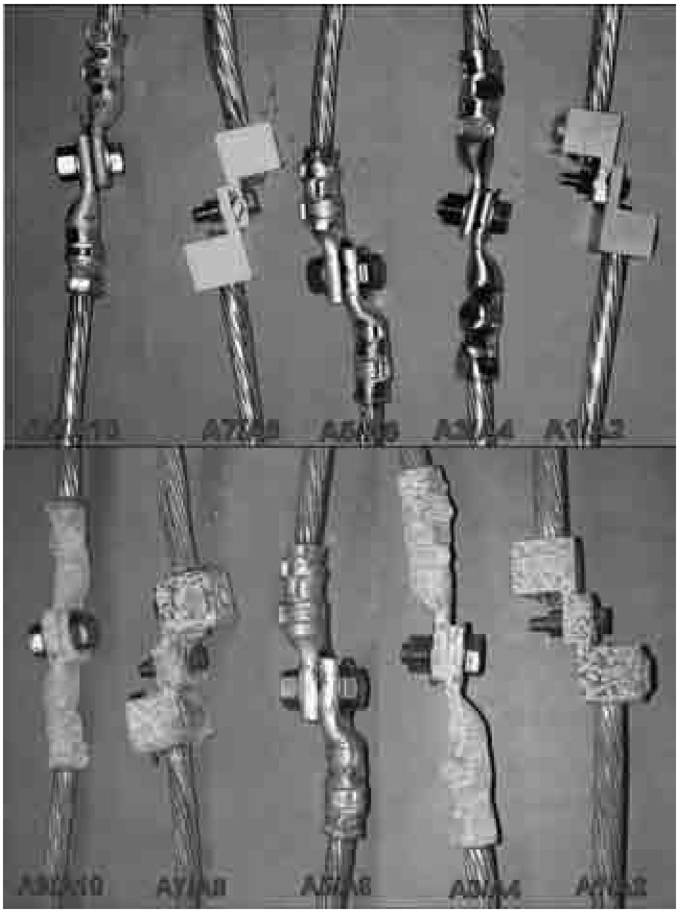


Figure 8. All-aluminum connections before testing (top) and after 2000 hours of environmental testing (bottom).

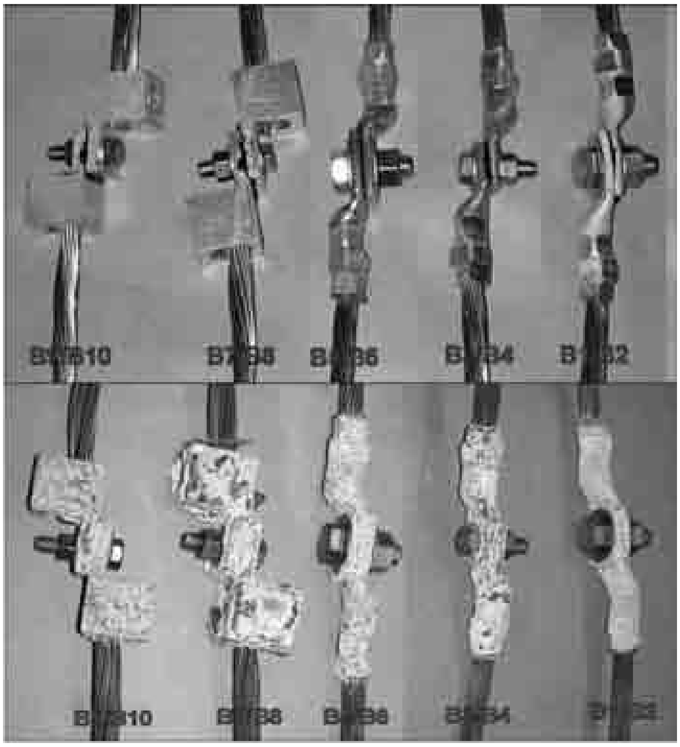


Figure 9. Aluminum connectors on copper conductor before testing (top) and after 2000 hours of environmental testing (bottom).

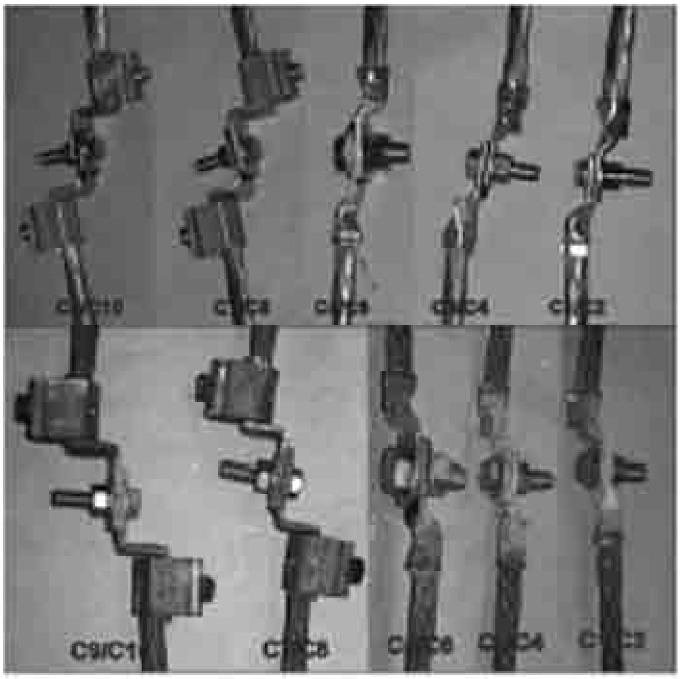


Figure 10. All-copper connections before testing (top) and after 2000 hours of environmental testing (bottom).

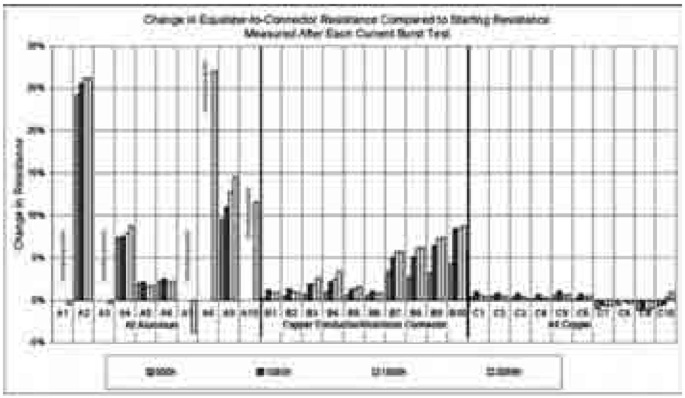


Figure 11. Percent change in resistance for all connectors compared to the resistance before testing, measured after each set of current burst tests.

The final results of the corrosion and current burst testing are given in Table II, which shows the number of samples of each type listed by percent change in resistance over the entire testing period.

Connector Type	Conductor Type	Overall resistance change compared to starting resistance:				
		-5% to 0%	*0% to +1%*	*+1 to +5%*	*+5% to +10%*	*>+10%*
Al	Al	3	0	2	1	4
Al	Cu	0	3	3	4	0
Cu	Cu	3	7	0	0	0

Table II. Number of samples of each type listed by percent change in resistance during the test

VII. CONCLUSIONS

The overall results for each connection type may be summarized as follows:

A. Aluminum connectors on aluminum conductor:

- 40% of the connector samples could be considered to have failed (>10% increase).
- 10% of the samples showed a significant increase in resistance (5% to 10% increase).
- 20% of the samples showed a moderate increase in resistance (1% to 5% increase).
- 30% of the samples showed a decrease in resistance.

B. Aluminum connectors on copper conductor:

- 40% of the samples showed a significant increase in resistance (5% to 10% increase).
- 30% of the samples showed a moderate increase in resistance (1% to 5% increase).
- 30% of the samples showed a decrease in resistance.

C. Copper connectors on copper conductor:

- 70% of the samples showed a small increase in resistance (0% to 1% increase).
- 30% of the samples showed a decrease in resistance.

The best performance in this 2000 hour corrosion and current burst test was attained by the all-copper connectors, which showed very little sign of degradation in electrical performance.

APPENDIX A

DETERMINATION OF CURRENT BURST LEVEL

A mechanical or compression high current connection relies on good asperity contact at the connection interface to maintain a low contact resistance. Asperity contact is maintained by the residual contact force on the connector, which is supplied by the screw fitting in a mechanical connector, or the residual stress in the deformed metal in a compression connector.

Under corrosive conditions, a poor connection may build up insulating oxides in the spaces between the asperities and at the edges of the asperities. High level, short duration current bursts are applied to the samples for sufficient duration to produce elevated temperatures at the asperity interface between the connector and conductor. The intention is to produce softening or melting of the asperities at the interface during the test. In a connector which has a build up of oxides, softening or melting at the asperities may cause loss of asperity contact if the residual force on the connector is insufficient to re-establish asperity contact with the oxide layer present. In an oxide free connection, the residual force can actually improve asperity contact when the asperities soften, resulting in a lower contact resistance.

The objective is to apply current bursts at a level which produces interface melting in a contact which has a high enough resistance to result in interface softening in the standard CSA C57 500-cycle connector test [4]. Therefore, the current pulse level is determined as follows.

According to Holm [2], the voltage drop across a contact is given by the following relation.

$$U_p^2 = 4L(T_I^2 - T_B^2) \qquad (1)$$

where:

U_p = peak voltage drop across contact

L = independent constant 2.4 x 10^{-8} $V2K^{-2}$

T_I = absolute temperature (K) of the contact spots in the interface

T_B = absolute temperature (K) of the bulk of the connector

A bulk temperature of 100°C is used in the calculation,

which is the maximum control conductor temperature used in the C57 cycling test. The RMS voltage, U_{rms}, is obtained by dividing the peak voltage by √2.

The magnitude of the current, I, required to produce either softening or melting at the interface is given by:

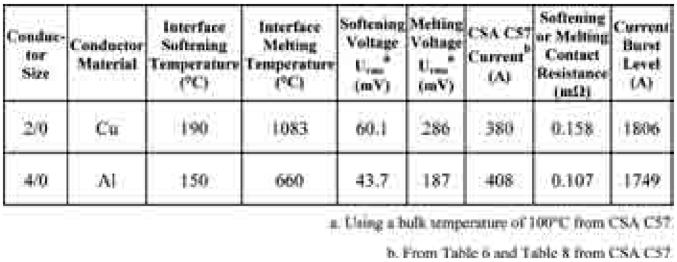
$$I = U_{rms}/R \qquad (2)$$

where:

R = resistance at which either interface softening occurs in the C57 test, or melting occurs in the current burst test.

The current burst levels calculated are given in Table III.

The calculation indicates that current levels of approximately 1800 Arms and 1750 Arms are suitable for copper and aluminum respectively.



Conductor Size	Conductor Material	Interface Softening Temperature (°C)	Interface Melting Temperature (°C)	Softening Voltage U_{rms} [a] (mV)	Melting Voltage U_{rms} [a] (mV)	CSA C57 Current [b] (A)	Softening or Melting Contact Resistance (mΩ)	Current Burst Level (A)
2/0	Cu	190	1083	60.1	286	380	0.158	1806
4/0	Al	150	660	43.7	187	408	0.107	1749

a. Using a bulk temperature of 100°C from CSA C57.

b. From Table 6 and Table 8 from CSA C57.

Table III. Calculated current burst levels

APPLICATION OF THE EL CID TEST WITH CIRCULATING CURRENTS IN STATOR WINDINGS

David Bertenshaw, John Sutton, ADWEL International Ltd.

ABSTRACT

EL CID tests are carried out to determine the integrity of the inter-lamination insulation in large stator cores. For the test ,the stator is excited by a winding that produces a circumferential magnetic flux around the core, and the EL CID test equipment analyses the resultant in-phase and quadrature magnetic potential difference values between adjacent stator teeth. The PHASE values are normally fairly constant around the core, but occasionally there are large and unexpected fluctuations in these values. It has been generally assumed that currents do not flow in the stator winding during EL CID tests and thus there was no satisfactory explanation of the large variations.

This paper reports on tests on a smaller turbo-generator and on a large hydro-generator where, in both tests, very large variations in the PHASE values were measured. By analyzing the presumed currents in the specific winding configuration, and in one test comparing to the same core without a winding, it is shown conclusively that in both tests the effect was caused by circulating currents induced in the stator winding by the EL CID excitation winding.

It is also shown that circulating currents do not adversely affect the uniformity of flux around the core, and that their effect on test results is eliminated by a simple analysis method. Thus circulating currents do not affect the efficacy of the EL CID test.

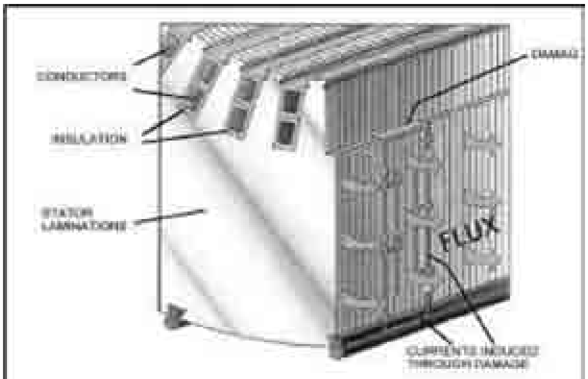


Fig 1 Eddy currents induced in a laminated core due to damage at the base of a slot

1. INTRODUCTION

The stator cores of AC electrical machines are built of thin laminations of magnetic steel, which are each coated with a thin layer of electrical insulation to prevent currents flowing between the laminations. If the insulation is damaged, the alternating magnetic flux through the stator core can cause eddy currents to flow between laminations (see Fig.1), leading to localized heating in the stator core and possible major breakdown.

It is thus important that the inter-lamination insulation remains intact in manufacture and service, and this requirement is well known to those involved in generator design and maintenance.

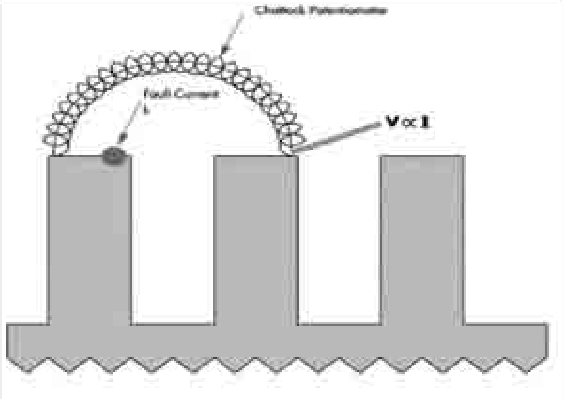


Fig 2 Chattock potentiometer positioned across Fault

2. PRINCIPLE OF THE EL CID TEST

The Electromagnetic Core Imperfection Detector test [Sutton, 1994] is now used world-wide as a trusted means of testing the integrity of inter-laminar insulation. To achieve this, the core is excited to a low level (normally 4% of operating flux) by a temporary excitation winding through the bore, and the fault currents induced in any damaged areas are measured by sensing the magnetic fields resulting from them. Since their magnetic field extends beyond the surface they can be detected by a Chattock potentiometer [Chattock, 1887] applied across the teeth of the core.

The Chattock magnetic potentiometer consists of a flexible, uniform, air-cored coil, which measures the magnetic potential difference (m.p.d.) between its ends. It is placed across the teeth, straddling a slot, and is scanned along the slot. Even in the absence of any fault in the core, a large m.p.d., in phase with the excitation current, is produced across the slot by the excitation current. This component, known as the PHASE m.p.d., is normally constant around the core and equal to Iw/N, where Iw is the excitation ampere-turns and N the number of stator slots. The Chattock also measures the magnetic field caused by any current flowing through a fault, such as shown in Fig. 2 on the tooth tip. Because of the resistance of the fault circuit, the current is substantially in-phase with the fault voltage and therefore in phase-quadrature with the excitation current. This quadrature (heat producing) component of the fault current, the QUAD m.p.d., is discriminated from the excitation m.p.d. by a phase sensitive detector, using the excitation flux as a reference.

3. CIRCULATING CURRENTS IN WINDINGS

Whilst it is quite normal to perform the EL CID test with the winding installed, it has generally been assumed that currents do not flow in the stator winding during the test. This conclusion is based on the expectation that an EL CID excitation winding, through the centre of the bore, generates only a circumferential flux around the stator core; thus no magnetic flux links the stator winding and no currents are induced in it.

However, there have been a number of unexplained results with large variations in PHASE and, to a lesser extent, QUAD, m.p.d. around the core, which were initially ascribed to extreme nonuniformity of the excitation flux density. If this were the case, the reliability of the EL CID test would be in question because fault currents are proportional to the local flux density. Ridley [Ridley, 2000] reports major circumferential variations in PHASE m.p.d. on several hydrogenerators with no satisfactory explanation. More recently, tests on a small turbo-generator and a large pumped storage hydro-generator, both with windings in place, also showed severe variation in PHASE m.p.d. around the core, even changing sign in places. In both these tests, there was no reason why excitation flux asymmetry could be so great that apparently flux reversal was occurring, thus it was concluded there must sometimes be substantial currents flowing in the windings.

If the excitation winding is wound through the centre of the stator bore, and if the core has a constant magnetic permeability around its circumference, the magnetic flux from the winding should be truly circumferential around the core. This is normally the case in tests on motors and turbo-generators. Since no net magnetic flux flows up or down the teeth, no flux links the stator winding and no currents are induced in it, even if closed paths exist. Currents will be induced only if there is asymmetry in the magnetic system that causes magnetic flux to flow radially, up and down the stator teeth.

Clearly, circulating currents are possible only if there are closed paths within the stator winding, i.e. if each phase has two or more parallel windings or if the three-phase windings are shorted together at both the neutral and line ends (e.g. through earth bonds) during the EL CID test. Parallel windings are found in both turbo and especially hydro-generators, and also in multi-pole motors, and the potential cause and effects of circulating currents are given below.

4. EFFECT ON A TURBO-GENERATOR

In turbo-generators, magnetic asymmetry is likely only if the excitation winding is not wound through the centre of the core. In this case, the excitation magnetic field is not circularly symmetric, and thus flux will flow up/down some teeth, linking the stator windings.

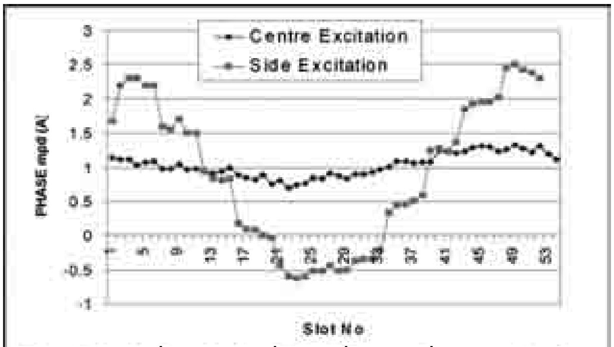
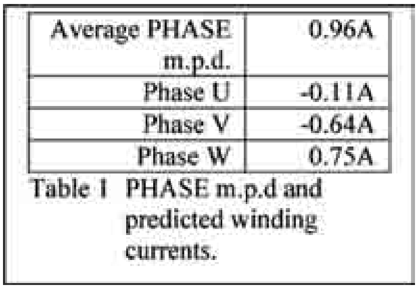


Fig 3 Variations in the PHASE m.p.d. across slots in a turbo-generator.

Large variations in PHASE m.p.d. were initially observed, but unexplained, on a 42MW, 11kV turbo-generator. The line ends of the windings were all bonded to earth, which connected the 3 phases in parallel since the neutrals were still all joined. The core was initially tested with the excitation winding resting against the side of the stator bore at slot 53 (for convenience since the bore was narrow), which gave dramatic variation in the PHASE (and QUAD) m.p.d. around the core. It was subsequently retested satisfactorily with the excitation winding through the centre of the stator as normally recommended.

Fig. 3 shows the variations in the PHASE m.p.d measured across the slots. (Due to the proximity of the excitation winding, no values were recorded for Side Excitation on slots 53 and 54). With the central excitation winding, the PHASE m.p.d. across each slot was almost constant around the core, whereas with the offset excitation winding there were large variations, including a substantial region where the m.p.d. was negative. Using the insight gained from the hydro-generator analysis reported below, the stator winding details were obtained, and are plotted graphically in Fig 4.



Average PHASE m.p.d.	0.96A
Phase U	-0.11A
Phase V	-0.64A
Phase W	0.75A

Table 1 PHASE m.p.d and predicted winding currents.

This shows by arrows where a phase current flows either “up” or “down” the slot, with one or two arrows indicating the number of bars carrying the current. For each phase (U, V, W), there are 8 slots that carry only the same winding in the same direction. Three phases, using the earth bonds as common points, the average PHASE m.p.d. around the whole core was

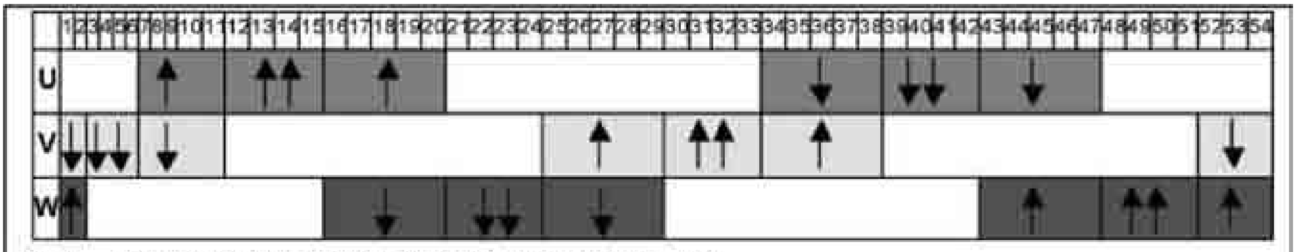


Fig 4 Diagram of phase winding layout in turbo-generator core

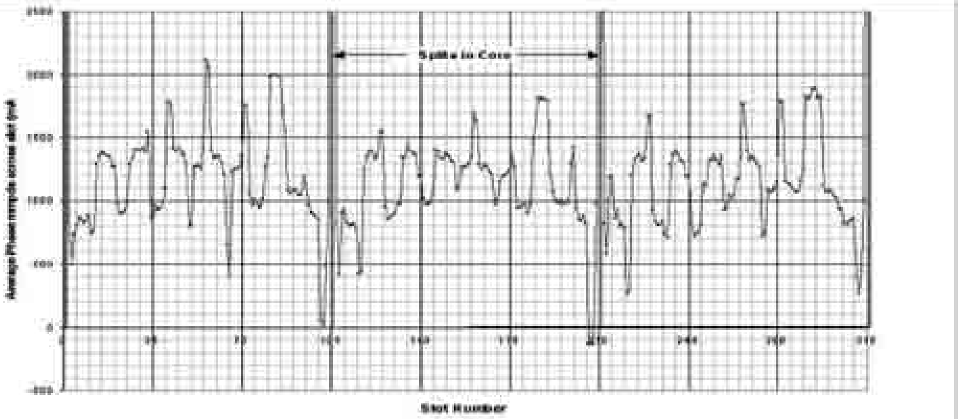


Fig. 6 Average PHASE m.p.d. measured across the slots of a hydro-generator with the stator winding installed.

evaluated, and from this, the currents flowing in each of the three phases were deduced, as shown in Table 1. It should be noted that the circulating currents sum to zero as expected, and that the average PHASE m.p.d. across the slots agrees with the test parameters (Iw /N = 8.5A x 6 turns / 54 slots = 0.94A).

The predicted PHASE m.p.d was plotted and compared with the measurements in Fig 5. The good agreement for the 8 slots per phase where the currents were deduced is, of course, to be expected. However, Fig. 5 also shows that the PHASE m.p.d. is closely predicted for all other slots. This demonstrates that the hypothesis that the effect is caused by circulating currents is valid.

Another rigorous experimental and theoretical study [Otaka et. al. 2004] also showed that currents can be induced in a large turbogenerator stator winding if the EL CID excitation winding is not installed through the centre of the stator bore, and that these currents are minimized if the excitation winding is correctly positioned.

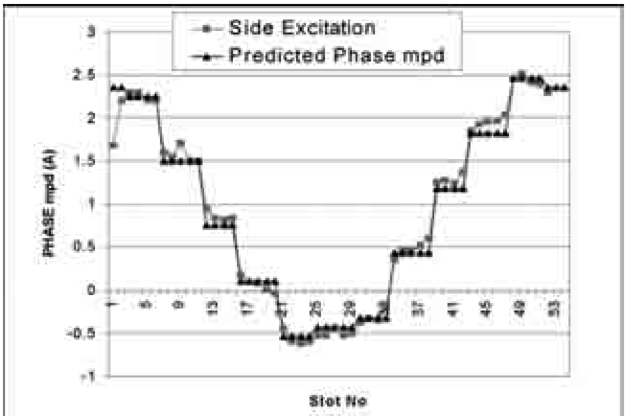


Fig.5 Predicted variations in the PHASE m.p.d. across slots in a turbo-generator from winding currents.

5. EFFECT ON A HYDRO-GENERATOR

Circulating currents in stator windings are more likely in hydro-generators because parallel windings are very common, and because it is not so straightforward to install the excitation through the centre of the bore. If, as is often the case, the windings are wound close to the bore at a few positions around the core, circulating currents may be induced in the stator winding. Circulating currents are particularly likely in large hydro-generators that are built up from sectors with small gaps between them. In the vicinity of such core splits, some of the circumferential flux escapes from the main body of the core to cross the gap, by flowing up and down the teeth either side of the gap, even if the excitation winding is central. This radial flux, up and down the stator teeth, links the stator winding and may induce significant currents in it.

Circulating currents may also occur if the test is conducted with the rotor still in place. If, for example, a small number of poles are removed, then asymmetric flux leakage will occur to the remaining poles, potentially inducing currents in any parallel circuits.

Two EL CID tests [Sutton et. al. 2004] were carried out on a large hydro-generator (300MVA, 12kV) with 7 parallel windings per phase and 3 core splits. The tests were made both before and after the stator windings had been fitted, and in both cases the excitation winding had been installed through the centre of the stator bore, thereby eliminating one cause of circulating currents. Without the stator windings, the measured PHASE m.p.d. between adjacent teeth was almost constant around the core, in the range 1.0 to 1.3A as expected. (Across the three splits the m.p.d. rose to about 10A also in line with expectation). With the windings in place, there were large variations in the measured PHASE m.p.d. across the slots as shown in Fig. 6, in the range ~0.0A to 2.2A, even well away from the splits. These were matched by smaller variations in QUAD m.p.d. as shown in Fig. 7.

It was also noticed that variation in PHASE potentials seemed to follow similar patterns around each of the three sectors of the core. This suggested that the effect was linked to the stator winding and that currents were flowing in it, contrary to expectation. The fact that the only known relevant difference between the two tests was that the windings were absent in the first test and present in the second, also strongly suggested that the large variations in the PHASE m.p.d were caused by currents induced in the stator winding.

To investigate the possibility of induced currents, the winding layout was studied in detail. Each of the three phases has 7 parallel windings, each with 30 bars (15 turns) in series housed in 315 slots. The layout of the three-phase winding in slots 150 to 250 is shown by the orange, yellow and blue boxes at the foot of Fig. 8. The number at the top of each box shows the designation of the parallel winding within each of the three phases and the colour of the box its phase. The arrows show whether the bars are connected such that the currents flow “up” or “down” the slots.

From Fig. 8 it can be seen that for every parallel section of the winding there is always a pair of “common” slots in which both the top and bottom bars carry the same current in the same direction.

These common slots are marked by small coloured boxes above the main boxes in Fig. 8 and they provide a means of

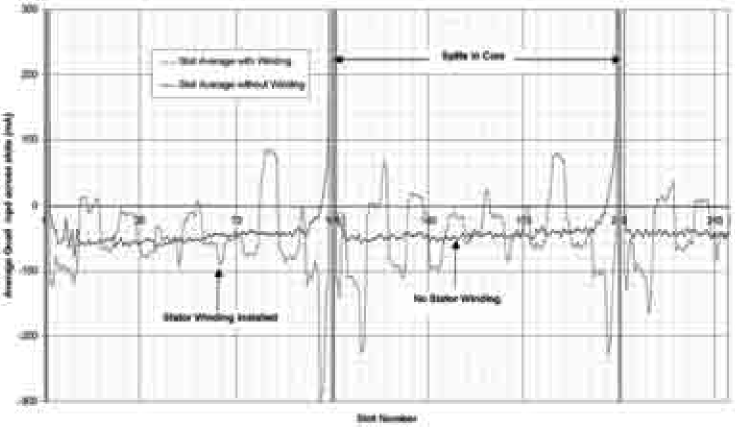


Fig. 7 Average QUAD m.p.d. across slots before and after winding installed (only slots 1 to 253 computed).

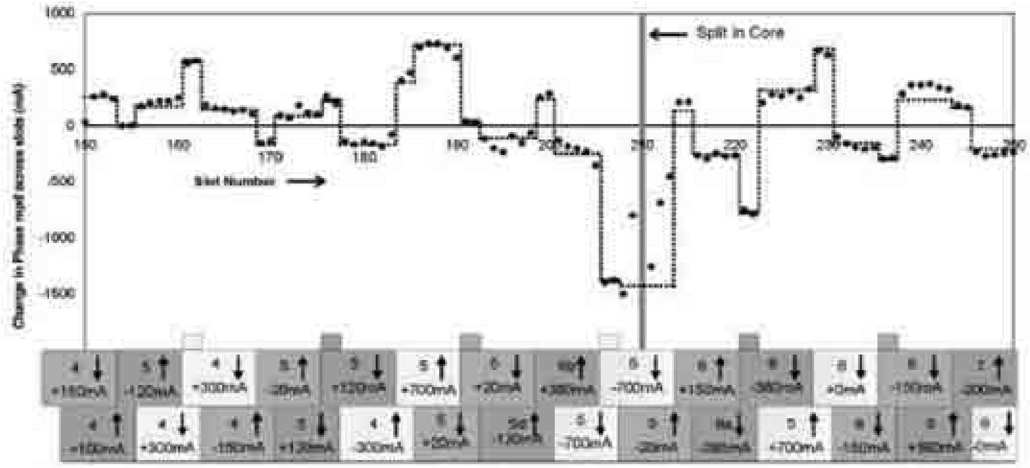


Fig. 8 The various boxes show the phase/parallel and connection direction, with common phase slots highlighted. The points along the dotted line show the measured values and the dotted line the predicted values.

determining the circulating currents. Since the currents in all sections of the stator winding can be determined by measurements on the common slots, the change in m.p.d. for the other slots can be predicted by vector addition of the currents flowing in the two bars in each slot. The m.p.d. shown in Fig. 8 are the changes in values caused by the presence of the winding and hence, according to our hypothesis, produced by currents circulating in the windings. Hence the total current flowing in each of the common slots is equal to the (change in) m.p.d. across that slot and the current in each conductor bar is 50% of the total current. These currents are printed in the boxes in Fig. 8, for the common, and other, slots. The predicted m.p.d, being the vector sum of the currents in the two bars in each slot, is shown by the dotted black line in Fig. 8. This line is seen to be close to the measured m.p.d. (blue circles) for all the slots. Hence the analysis of the data in Fig. 8 confirms the hypothesis that the variation in the PHASE m.p.d. across slots was solely caused by circulating currents induced in the stator winding by the EL CID excitation winding.

Further proof that currents were induced in the stator winding was provided by bending a Chattock potentiometer around some of the bars where they emerged from the slots and so obtaining a rough measure of currents flowing through them. The measured currents ranged from 200mA to 600mA, consistent with the values determined by the above analysis.

The uniformity of the flux in this core was confirmed by measuring the voltage induced in a single turn of wire around the core close to a gap and then near to the centre of a sector. The voltage induced in the turn, and hence the flux in the core, was virtually identical at the two positions.

6. IMPLICATION FOR EL CID TESTS

It is good practice, after setting up an EL CID test, to measure the PHASE m.p.d across a number of slots around the bore, and to check that they are approximately equal to the value that is normally expected (Iw/N). If these values are found to vary considerably, then this probably indicates that currents are being induced in the stator windings (rather than an inconsistency in the stator core or equipment).

Circulating currents induced in stator windings need not cause a problem in the analysis of EL CID results. This is because the currents are constant along the full length of each slot and they simply produce a constant signal offset (DC component) in the measured PHASE and QUAD traces. The offset in the QUAD m.p.d. is a simple addition/subtraction to all the normal values, and may thus be readily removed by using the "Remove DC Components" option incorporated into the analysis software. If this facility is used for the QUAD traces, this then allows any localized QUAD change indicative of a fault to be assessed.

To demonstrate the effectiveness of this approach, the following graphs in Fig. 9 show traces from four of the slots measured on the hydro-generator mentioned above. The traces show the QUAD m.p.d. measured before and after the stator winding had been installed. For both sets of traces, the EL CID analysis software (ELAN) was set to "Remove DC Components", thereby eliminating the constant m.p.d. along each slot caused by circulating currents. The traces are almost identical, demonstrating that the effective analysis of EL CID traces for core defects is unaffected by winding currents.

However, it is recommended to arrange the test and exci-

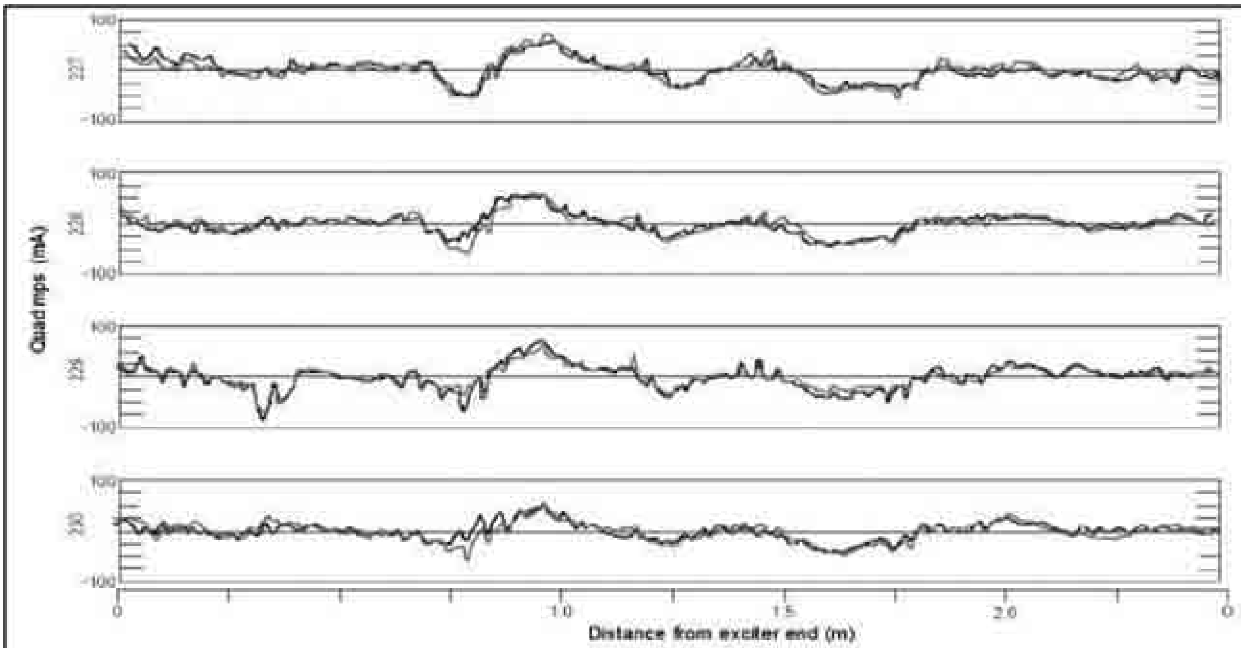


Fig. 9 QUAD m.d.p. for four slots of a Hydro-generator with no winding (light traces) and with its winding (dark traces) which was carrying large circulating currents.

tation to minimize circulating currents as far as possible, for the following reasons:

- It is good practice to reduce disturbing "noise" in any measurement system to maximize the signal quality and integrity.
- Local high amplitude PHASE m.p.d. may cause the EL CID signal to over-range unexpectedly. Use of a higher current range will reduce the sensitivity to all signals.
- It is more difficult to reliably set the phase of EL CID's Phase Sensitive Detector ("Phase Reset").
- It is not possible to observe true QUAD signals during a test, since offsets can only be eliminated after the test.

It is important to ensure that the EL CID Phase Reset is done while the Chattock is in a region that is free of circulating currents. If this is not done, the Phase Reset will be affected by the phase angle of these currents, and genuine core fault currents may not be fully or correctly resolved. For example, in the hydro-generator case above, the phase angle of the circulating currents was about 9°, thus if a region with high circulating current had been chosen for a Phase Reset, this offset would have been introduced into the EL CID phase reference. In subsequent testing 15% of any PHASE signal would have been resolved as a QUAD signal, reducing the QUAD accuracy and potentially distorting the QUAD variation with any PHASE variation.

If a region without circulating currents cannot be found, then the Phase Reset may be done with the Chattock in the Calibration Unit, or the Chattock held near the energized excitation winding, away from the core surface. Both these methods will lead to a small constant QUAD signal on areas of good core, but the phase angle error will be small and any resolution error insignificant. The "Remove DC Components" function will remove any such constant QUAD signal as well as the effects of any circulating currents.

7. CONCLUSIONS

In the past, unexpected and unexplained variations have been observed in the PHASE m.p.d. measured across stator slots during EL CID tests. It had been suggested that the variations could be caused by serious non-uniformity of magnetic flux around the core, which would cause difficulty in interpreting the test results. This paper shows that the variations are caused by currents circulating in the stator windings, induced by the EL CID excitation winding. These currents can occur both in turbogenerators and, more commonly, in hydro-generators, where parallel circuits exist or are formed when the phase windings are shorted together for the test. Smaller variations and offsets occur also in the measured QUAD m.p.d. but do not affect the efficacy of EL CID test results.

Existing software enables the offsets to be removed and the underlying core condition, as expressed by the QUAD m.p.d., to be clearly seen. Simple guidelines allow the EL CID test to continue be used with confidence.

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IMPORTANT MEASUREMENTS THAT SUPPORT INFRARED SURVEYS IN SUBSTATIONS

Robert Madding, Infrared Training Center FLIR Systems, Ken Leonard, Carolina Power & Light and Gary L. Orlove, Infrared Training Center, FLIR Systems

You have found a hot spot in a substation with your Infrared (IR) camera, also known as a thermal imager. You know it is a problem, and you must now determine just how bad it is. Does it need to be fixed immediately, or can it wait a few days, a few weeks? What other useful information could you measure while in the substation? Two very important measurements are load and wind speed. Both strongly affect the apparent severity of a problem. In a ring-bus, or parallel bus system, knowing the current in each side is crucial to making the proper call. This paper discusses making these measurements safely using inexpensive instrumentation that is currently available.

Keywords: Power loss, load correction, infrared surveys, infrared, thermography, substation thermography, wind correction.

1. INTRODUCTION

Substation IR surveys are an efficient means of identifying problems under energized operating conditions. There are hundreds to thousands of connections in a substation depending on its size. Making individual measurements on each one would be prohibitively time-consuming. Modern infrared cameras, also referred to as thermal imagers do a great job of spotting problems when in the hands of the well-trained thermographer, one who understands direct and indirect measurement, emissivity, distance, load, environmental and other parameters that impact what the thermographer sees through the eyes of the IR camera or thermal imager. But not every problem needs fixing right away. Some can wait; others cannot. After acquiring good IR data and finding problems, their severity is the greatest challenge facing the thermographer.

Experience goes a long way in the problem severity arena. But measurements that support the thermal imager data can be very useful in assessing how bad the problem is. Load is crucial. A 45 F temperature rise, direct reading, under 50% load is a much more severe problem than the same temperature rise under 90% load. This temperature rise measured in a 10 mph wind is much more severe than in no wind. Both wind and load effects are discussed in detail in other publications (1, 2, 3). Other environmental parameters such as solar load, air temperature and humidity play lesser, but still important roles.

2. SAFETY CONSIDERATIONS

People who walk in the woods have no idea of the power stored in the mass of a tree. A lumberjack felling such a tree gets a real hint when the tree hits the ground, the earth shakes and a large, long dent is left behind. One who cuts this tree into smaller sections for firewood and carries them out by hand gets a real feeling for the tremendous mass of even a fairly small tree. They look harmless, just standing there. But if one falls on you, you're dead.

Electric power also appears harmless. It's not snarling, roaring or hissing, all prehistoric danger signals we humans have learned to recognize for our survival. Electricity is just there, not obviously dangerous. We must learn through training how to stay alive in this seemingly benign, but potentially deadly environment. High voltage is unforgiving. You don't get second chances.

For substation work, never enter a substation without being accompanied by qualified personnel. Always have a tailgate meeting before starting your IR survey. Learn and follow their rules. Discuss their problem severity criteria. Wear proper safety equipment. Hard hat and safety glasses are universal. Some utilities require long sleeve cotton shirts and leather shoes. Others may only require short sleeves. Find out clothing requirements before you go there.

Use your senses to get a first reading on the health of the substation. Sniff for oil, listen for arcing, look for obvious problems, such as a wire on the fence. Use your IR camera, also known as a thermal imager to get an initial overview of the substation. Do a quick look for major problems. If you find a critical problem, you may need to "freeze and leave". That is, freeze and save the image, then leave the area to a safe location. The substation electrician or qualified host will want to contact the proper personnel to take action on such a critical problem. What you do not want to do is ask everyone to "come and look at this thing that is about to blow up!"

Usually, you don't want to extend anything above your head. We often do this to measure wind speed as the wind speed can be different at the target. Get permission from the substation qualified person as to where you may perform such activities. Let the qualified person open control cabinets and operate any controls or buttons. (Often, loads can be read out digitally if you know how to access the data.)

Learn how to do IR surveys in substations. This paper is an adjunct to basic substation IR survey training. You should be able to identify the components, have a basic understanding of their function and purpose, know what to look for, know where the indirect measurements are, have a fundamental understanding of equipment criticality, and know a dangerous situation when you see it.

Figure 1. Ketrel 3000 pocket weather meter

3. MEASURING AND CORRECTING FOR WIND SPEED

The Kestrel 3000 wind meter, Figure 1, is used by many thermographers to get wind speed, air temperature, and relative humidity. It also gives dew point temperature, wind chill and heat index. It is a pocket size instrument and sells for about $150. Wind speed can dramatically affect hot spot temperature and associated temperature rise. A 3 mph wind can cut the temperature rise in half from no wind conditions! A simple wind speed correction factor doesn't exist as the correction depends on the watt loss of the hot spot. Correcting for wind speed on "direct" targets can be done using Figure 2, taken from reference 1. To do this accurately, you would multiply the resistance of the directly read hot spot by load in amps squared to get the watts of power (I2R) being dissipated as heat. Figure 2 gives three power values, 7.9, 18 and 27 watts. You could roughly interpolate between these values. For example, for a resistance of 250 micro-ohms, 230 amp load, the power loss is 13.2 watts. For a 10 mph wind, the correction is about 3.5. You could multiply the measured temperature rise by this value to get the corrected value.

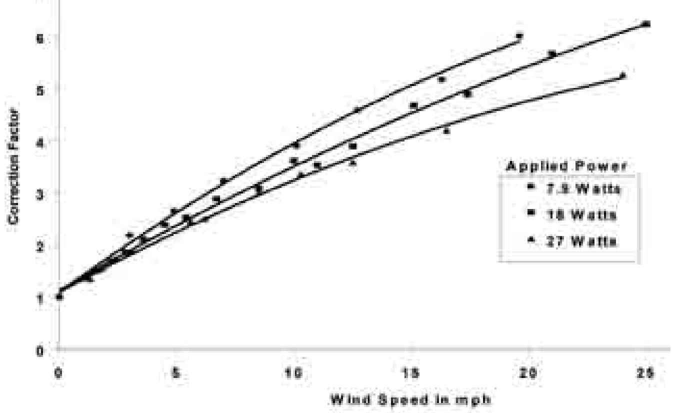


Figure 2. Wind speed correction factor vs. wind speed for various power levels. From reference 1.

The following considerations are why it is difficult to get accurate temperature rise corrections under windy conditions:

- Considering the uncertainties in emissivity and background, your initial temperature estimates can have fairly wide error bars. Does it make sense to go to a lot of work to accurately correct an already uncertain measurement?
- Load and wind speed are related. The correction depends on load. Do you correct for existing load, or do you correct for maximum load?
- Knowing the wind speed at the component is also problematic. The Kestrel does a great job of measuring at its location. But the wind can vary significantly from that point to the part in question.
- What wind speed value do you correct to? You need to correct to the minimum wind speed expected under load conditions, not necessarily zero wind speed. If the wind is always blowing, and there are areas where this is the general case, what is the lowest value?
- Getting the connection resistance is problematic. And once you know the connection resistance, you already have enough information to make a call on severity.

Our heads were spinning when we realized all the drawbacks to wind speed correction. Trying to get accurate wind correction on these measurements doesn't necessarily make a lot of sense. But multiplication factors of 3 or 4 are not small corrections and need to be recognized at some level. Familiarize yourself with the chart. Get some idea of the minimum wind speed in your area. Recognize that wind can play a major role in cooling a component. Try to get measurements under minimum wind conditions. Avoid doing thermography in high wind conditions.

Should you estimate a wind speed correction every time? No. If the temperature rise is already fairly high, and the load is nominal, you know that at full load and no wind, the temperature rise will be significantly higher. Or, if the temperature rise is already at the critical level, the correction cannot push it to a higher level.

Wind speed correction is useful for those nominal temperature rises, like 30° F. This doesn't sound too bad for a direct measurement. But if measured in a 10 mph wind, the corrected value ranges from about 90° to 120° F, if you are correcting to zero wind speed. It is often very important to make a wind speed correction estimate.

4. LOAD MEASUREMENT

Load (current) is very important for the thermographer. Heat is generated in a bad connection by electric current flowing through a resistance. The power loss can be calculated as shown above. It is directly proportional to the square of the load. But temperature rise is not directly proportional to the square of the load. It follows a more complex pattern as discussed below.

But if you don't know the load, you can be completely in the dark about problem severity. Again, if you find a very high temperature rise, one that exceeds the critical or upper limit of your severity criteria, you don't need to know the load. For problems that uncorrected are not critical, knowledge of the load is crucial. You need to know both the actual load and the maximum load to do a proper evaluation.

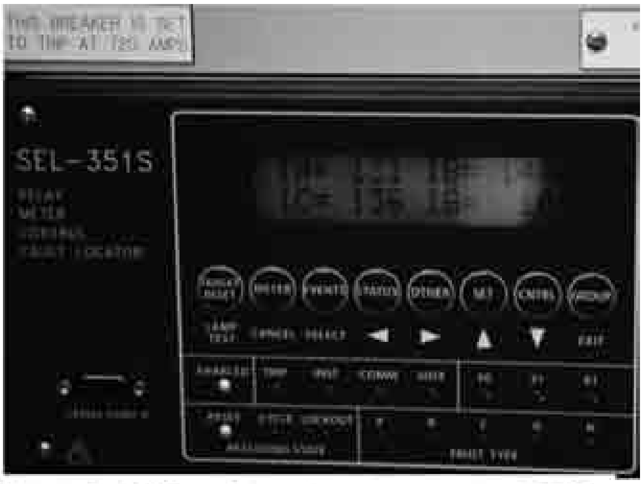


Figure 3. LCD readout of amperage on an OCB control panel.

For a ring bus problem, measuring the load can save someone's life. Unfortunately (or fortunately for the utility), we did not find a ring bus problem to give as an example in this paper. Earlier work (4) prior to our ability to measure the load directly in the switchyard, gave an example where 1200 amps entered the ring bus, and by calculation we determined 1050 amps flowed through one leg and only 150 amps flowed through the other. If the operators did not know this, they could well open the "good" side and attempt to force all 1200 amps down the "bad" side. The measured resistance of the bad connection that shunted most of the current down the other side was 96,000 micro-ohms. Opening the good side would cause 1200X1200X0.096=138,240 watts to be dissipated in the bad connection. The result would have been catastrophic. We recommend never opening one leg of a ring bus when you know you have problems, without first measuring load in both sides of the bus.

How do you get load in a substation? Often, control cabinets have a readout that gives the current for each phase. Figure 3 gives an example. Or, you may be able to contact the control room and get a load reading from them. Basic electricity says that all the current that flows into a wire flows out of the wire, so this value is valid as long as the conductor doesn't split, as in the ring bus example above. When this happens you cannot assume a 50/50 split in the current flow. It depends on the resistances in each side of the parallel circuit.

For these cases and when no readout is available, you can make your own measurement with a portable ammeter on the end of a hot stick. We used the Ampstik shown in Figure 4. The ammeter attaches to the end of a telescoping hot stick. The reading is stored and read out when retrieved. Newer models will store several readings so you don't have to retrieve the meter each time. Figure 4 shows a typical measurement. Proper training is required for measuring high voltage live line current. Only qualified personnel should do this!

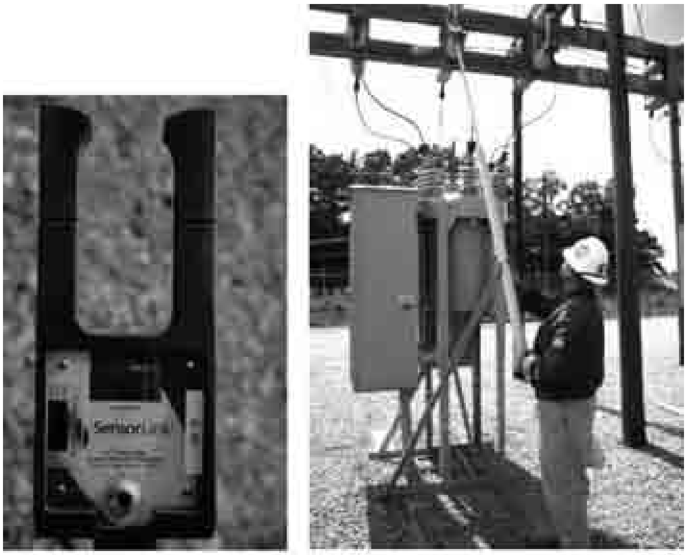


Figure 4. Close-up of the Ampstik and in use to measure one side of a switch.

Figure 5 is the IR image of the B-phase and C-phase of a 23 KV line side disconnect. The switches have an inverted Y configuration, so there is a parallel path between the hinge and the jaws. In both cases, the left side hinge is hot while the right side is cool. We measured the current through each side of each phase and found almost all the current was flowing through the left side of both the B- and C-phase switches. We interpret this as both sides of the hinge are bad on both switches. The right side is much worse than the left side, forcing most of the current through the left side. We also found the current beginning to become imbalanced in the A-phase switch, which may indicate an impending problem. We recommended all three switches be repaired or replaced.

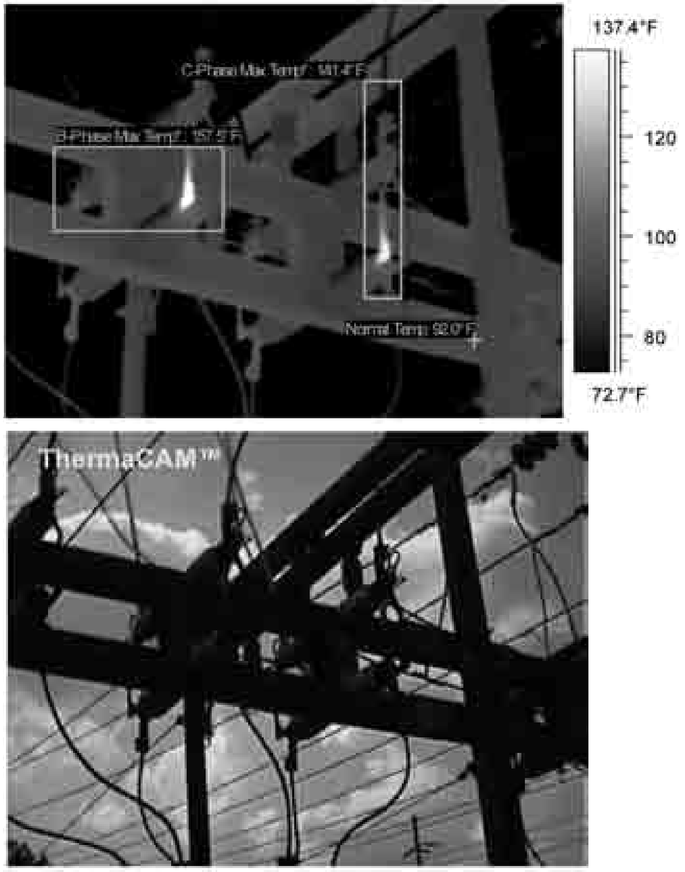


Figure 5. Thermogram/photo pair showing problem line side 23 KV OCB switch disconnects on B- and C-phases.

Once you have determined the load, you need to find what percentage of maximum load it represents. To do this, divide the measured load by the maximum load and multiply by 100 to get per cent.

In this case, we must consider two maximum loads. One is a "normal" maximum that can occur daily during hot weather. The other is a "two feeder" maximum where due to other problems two OCBs are fed through these switches. In the following section, we will use this as an example for load correction of temperature rise.

23 KV Oil Circuit Breaker Line Side Switches					
Phase	Left Side Amps	Right Side Amps	Total Amps	% Load Normal Max 275 Amps	% Load Two Feeder Max 525 Amps
A	69.8	129.5	199.3	72%	38%
B	195	1.8	196.8	72%	37%
C	193	2.0	195	71%	37%

Table 1. Measured current on inverted Y switches, each leg and total.

5. LOAD CORRECTION

There have been many attempts to derive a simple load correction factor where the temperature rise for a known load is multiplied by a number to give the full load temperature rise. In this way, the severity of the problem can be evaluated for full load conditions. Or, one could calculate the load that would give the maximum temperature rise for safe operation.

The power dissipated as heat equals the square of the load times the electrical resistance (P=I2R). One might then expect the temperature rise to vary as the square of the load. If the load doubled, the power dissipated increased by a factor of 4, and the temperature rise increased likewise. For heat transfer by conduction alone, this is valid. But heat transfer by radiation depends on temperature to the fourth power (T4 Stefan Boltzmann Law). Convection as well is dependent directly on temperature rise only in limited regions. Both play an important role in electrical problem heat dissipation. The square assumption predicts a much too high rise, and should not be used (2, 3).

One might assume the temperature rise (Delta T) increases as some power of the current and so attempt to fit Delta T=InR, where the current is raised to the nth power, n being determined by fitting data or modeling. Perch-Nielsen et al (3) did some experiments and found n varied between 0.6 and 2 depending on conditions.

We used the power loss software (5) to calculate the effects of changing load for various emissivity targets, air temperatures and background temperatures. We fit the resulting data to the above equation to find n for various conditions. Our modeling shows there is no single value for n for all cases. There is no simple load correction factor. We found a range of exponents (n-values) from a high of 1.6 to a low of 1.46. Our modeling considered a low emissivity target (minimum of 0.6) to a high emissivity target (maximum of 0.95) with an air temperature of about 70 F and background temperature ranging from 70 F to -13 F. The simulated target was 4" wide by 1" thick by 6" tall. The value of n decreases as heat transfer by radiation increases due to its non-linear, T4, nature. Strongest radiation occurs for high emissivity, low background targets.

Figure 6 shows our modeled estimates for limiting conditions that will give the thermographer a reasonable idea of the multiplication factor to use for full load correction (values of n are given in the legend). These are "middle-of-the-road" results compared to others referenced above. But they do represent the bounds of what we found with our modeling. The factors are not small, and like the wind correction can make a huge difference in your severity estimates. Figure 6 also shows that performing IR surveys under low load conditions leads to greater uncertainties in predicting the temperature rise at full load conditions.

As the graph is in log-log format, it is a bit tricky to estimate the values between gridlines. For those mathematically inclined, you can calculate the value as follows: Multiplier = (1/%load)n. For example, at 50% load, the maximum correction (n=1.6) would be (1/0.5)1.6= 21.6=3.03. Many calculators have the yx function to do this type of calculation, but, as these are estimates, it is simpler to look at the chart and estimate the value.

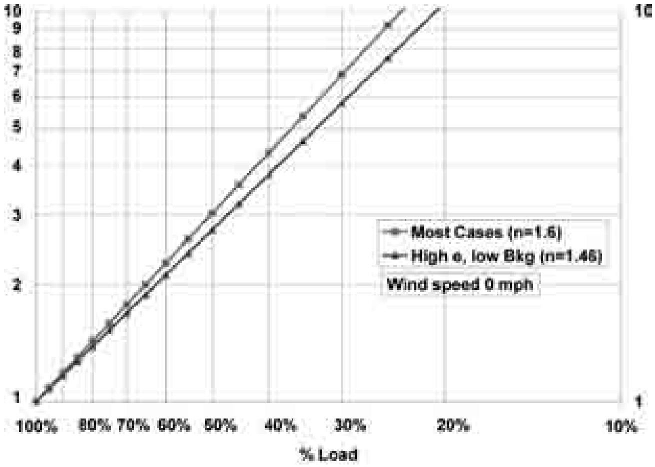
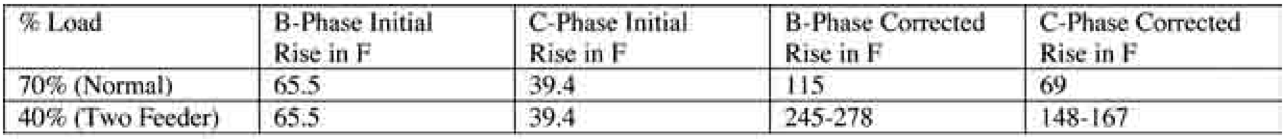


Figure 6. Load Correction. Multiply temperature rise by factor given at measured % load to correct to full load conditions.

Let's use the load correction chart to estimate the temperature rise of the hot switch components shown in Figure 5. The B-phase shows a 65.5 F rise, the C-phase a 39.4 F rise. Wind speed was 0 mph. For the normal full load condition, the load is about 70%. The correction factor read from Figure 7 is about 1 3/4, so the normal full load corrected temperature rises would be about 115 F and 69 F, respectively. For the two-feeder full load condition, load is about 40% and correction factors range from about 3 3/4 to 4 1/4. Corrected temperature rises are then about 245 to 278 F for the B-phase and 148 F to 167 F for the C-phase. Table 2 summarizes our estimates.



% Load	B-Phase Initial Rise in F	C-Phase Initial Rise in F	B-Phase Corrected Rise in F	C-Phase Corrected Rise in F
70% (Normal)	65.5	39.4	115	69
40% (Two Feeder)	65.5	39.4	245-278	148-167

Table 2. Raw and full-load corrected temperature rises.

These corrected temperature rises give the thermographer excellent information about what to expect when the load goes up. They can be used to help evaluate risk of going to higher loads.

So, even though we still don't have the complete story on load correction, we strongly recommend thermographers consider the range of values for temperature rise that could be realized as the load increases. The load correction curves are for zero wind conditions. Trying to correct both for wind and load can be problematic, as they are related. We recommend not performing IR surveys in low load, windy conditions. You will miss some problems, and correcting for those you do find can be difficult. If you must go out in those conditions, plan to return as soon as the wind goes down and/or the load goes up.

6. SUMMARY

Wind speed and load are two important measurements in addition to your IR camera or thermal imager data when working on electrical systems. Though written with substations in mind, the work is equally valid for other areas such as distribution and transmission lines.

Measuring wind speed and load in a substation is a lot easier than correcting temperature rise data for them. This paper shows the correction factors in both cases are large, so even though we do not have all the answers at this point, the wise thermographer will do well to consider their significance. Further research and experimentation needs to be done to help quantify these factors and provide thermographers with even better correction tools. Be very wary of simple wind or load correction factors. They don't exist at this time.

For a ring bus, or parallel circuits, problems found with IR should be backed up with load measurements of each parallel leg. It can occur that a major problem is shunting so much current it appears cool whilst a smaller problem in the other leg shows hot due to the high load it is carrying from the shunted current. Safe practice says measure the load and be sure. The switch example illustrates this, though safety was not an issue in this regard as both legs of the switch would open at the same time.

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3. Perch-Nielsen T., Sorensen, J.C.; "Guidelines to thermographic inspection of electrical installations"; pp 2-13; Proc. Thermosense XVI; SPIE Vol. 2245; April, 1994

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USE OF AN ISOLATION TRANSFORMER WHILE PERFORMING LINE LEAKAGE OR FUNCTIONAL RUN TESTS

Associated Research, Inc.

Associated Research strongly recommends the use of an isolation transformer or isolated power source for powering up the Device Under Test (DUT) when performing the Line Leakage or Functional Run tests. This article covers the various reasons for isolating the DUT power source during these types of tests.

SAFETY

First and foremost, we need to always consider minimizing the operator risk for electrical shock during any safety testing. Using an isolation transformer or an isolated power source can greatly reduce the potential shock hazard for the operator. Some Line Leakage standards direct the operator to cycle the power switch of the DUT on and off. Contacting the DUT under an open ground condition could expose the operator to a potential shock hazard as the enclosure of the DUT can have a voltage induced on it that is referenced to earth ground. This could be hazardous since the operator is also grounded. For this reason, it is suggested that an isolated power source be used to power the DUT. If the output of the power source is not earth ground referenced, then the shock hazard from contacting the case of the DUT and earth ground is eliminated. Figure 1 shows a circuit that incorporates an Isolation Transformer that is the preferred method. The current leakage path to earth ground has been eliminated with the use of the isolation transformer. This effectively eliminates the shock hazard.

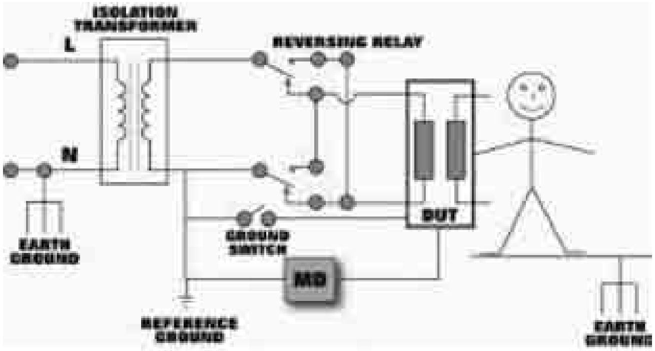


Figure 1

GROUND LEAKAGE

Every DUT that is powered from AC line power is going to have a certain amount of leakage back to earth ground, since power distribution systems are ground referenced.

Much of the leakage seen during a Line Leakage test can be due to the distributed capacitance of the DUT and the applied voltage. Figure 2, shows a Line Leakage test circuit where the neutral is referenced to earth ground. With this configuration any internal leakage in the test instrument and fixture is added to the leakage of the DUT.

Since most Line Leakage testers are powered from the line there will always be some internal leakage in the Measuring Device (MD) circuits. Associated Research has designed our testers to minimize the effect of this ground leakage, but it is impossible to reduce this leakage to zero without isolating the DUT power source. Figure 3 shows the same test circuit but incorporates the use of an isolation transformer for DUT power.

Performing the test in this manner greatly reduces the internal leakage making this a more accurate test.

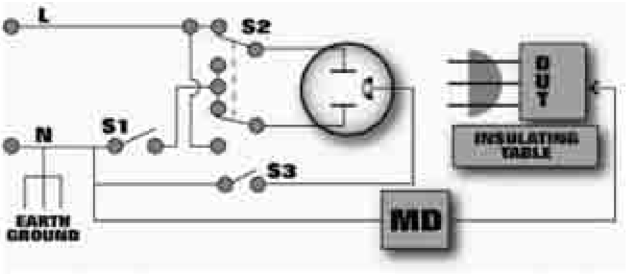


Figure 2: Enclosure Leakage Test Neutral Referenced to Earth Ground

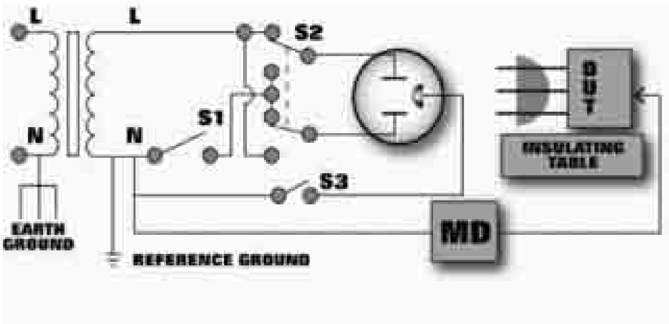


Figure 3: Enclosure Leakage Test Isolated Input, The Output of the Isolation Transformer is not Referenced to Earth Ground

OVER-VOLTAGE

When performing a Line Leakage test, many product safety standards require manufacturers to apply a test voltage that is equal to 110% of the specified input voltage for the DUT. Obviously if the DUT is simply plugged into a wall receptacle, then the line voltage is not variable and this requirement cannot be met. For this reason, in order to meet this requirement of testing at a slight over-voltage, the DUT would have to be powered by a power source with a variable input.

NOTE: Many of the diagrams shown in the safety standards show the neutral side of the line as a ground reference point. This does not mean a connection should be made between the neutral and the common earth ground. If you were to connect the neutral of the power source or isolation transformer to earth ground, you would, in effect, be defeating the entire isolation of the circuit. These illustrations in these specifications simply point out that the neutral side of the line is the ground reference point for your leakage measurements for some of the tests that are required, it is not an earth ground reference.

TEST INSTRUMENT PROTECTION

Finally, we are recommending that an isolation transformer or an isolated power source be used as the source of supply for powering up the DUT whenever a Functional Run test or Line Leakage test is being performed at the same test station as the Hipot test. This is a precautionary recommendation to provide protection for the Hipot tester that may be inadvertently connected to the DUT while line power is applied. It is possible that the return circuit on a Hipot tester can be damaged when left connected to the DUT during a test when a line-to-ground fault condition exists. The return circuits of a Hipot tester are not designed to carry the high fault currents that can exist when a line-to-ground fault condition occurs during a line powered test. In many cases, the return circuit of the Hipot tester may actually be the low resistance path for the fault current to flow back to ground.

Another way to avoid this is to always perform the Hipot test prior to a Functional Run or Line Leakage test. The Functional Run or Line Leakage tests should only be performed after a Hipot test has successfully been completed, as the Hipot test will detect line-to-ground faults before line voltage is applied to the product. In addition, we recommend when using multi-functional instruments that include the capability to bypass failures on multi-step tests, that this function be de-activated so that the instrument will not advance from a failed Hipot test into a Run or Line Leakage test where a line to ground fault could have caused the Hipot failure. These techniques, in addition to the use of an isolated power source, will help to avoid blowing fast acting fuses that are built in to the product design to protect the instrument from the high in-rush current that can result from a line to ground fault.

MEASURING MAGNETIC FIELDS
ELECTRIC AND MAGNETIC FIELDS

Australian Radiation Protection and Nuclear Agency

Everything electrical, from a toaster to a high-voltage power line, produces electric and magnetic fields. Both the electric and magnetic fields are strong close to an operating source. The strength of the electric field depends on the voltage and is present in any live wire whether an electrical appliance is being used or not. Magnetic fields, on the other hand, are produced by electric currents and are only present when an appliance is operating, i.e. there is no magnetic field when an electrical appliance is turned off.

HEALTH EFFECTS

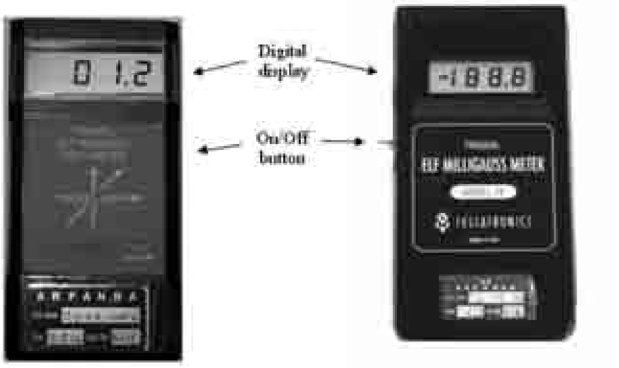
Currently there is no evidence that exposure to electric fields is a health hazard (excluding electric shock). Whether exposure to magnetic fields is equally harmless, remains an open question. A large number of scientific studies performed on animals and cells have not found a health risk. Some epidemiological studies, however, have suggested a weak link between intense and prolonged exposure to magnetic fields and childhood leukaemia.

MAGNETIC FIELD UNITS

The strength of the magnetic field is expressed in units of Tesla (T) or microtesla (μT). Another unit, which is commonly used is the Gauss (G) or milligauss (mG), where 1 G is equivalent to 10^{-4} T (or 1 mG = 0.1 μT).

THE GAUSS METER

There is a range of different instruments that can measure the magnetic field strength. The gauss meter is a hand-held device that provides a simple way of performing such measurements. ARPANSA has two different gauss meter models available for hire, which are a Teslatronics Model 70 and a Sypris Model 4080. Both these instruments operate in a similar manner and they are shown in the figure below.



Both gauss meters measure alternating fields from 25 Hz to 1000 Hz in units of mG. They do not measure and will give false readings from mobile phones. Readings taken very close (a few cm) to other electronic devices (as distinct from electrical devices such as heaters, washing machines etc) may also give false readings. Shaking or vibrating either unit may also give false readings. Since the meters only measure varying magnetic fields, they will not measure the earth's magnetic field which is static and has a value of approximately 500 mG.

When either meter is turned on, it will perform an initial self-diagnostic test by showing all available readouts on its digital display. Following the initial test, the meter will display the magnetic field intensity at the location where it is held or placed and the intensity will change if moved accordingly. If the negative sign is still showing after the initial test, that indicates that the meter is running low on power and the battery needs to be replaced.

PERFORMING MEASUREMENTS

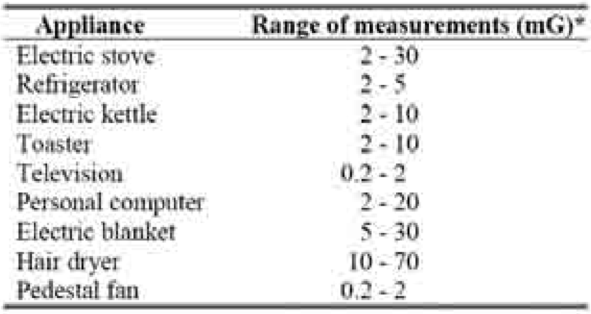
Measurements of the magnetic field in the home are generally taken in the middle of the room at about one metre from the ground or in locations where people spend a significant amount of time, for example, the bed. Measurements should also be performed several times over the course of a day. This is to allow for possible variations to electricity demand which presumably would peak during the evening at about 7.00 pm. Measurements can also be made at any other locations of interest.

It is important to remember that, as mentioned earlier, research suggests that if any health effects exist, they are associated with prolonged magnetic field exposure. Measurements taken with the gauss meter are instantaneous (i.e. measured at one point in time) and do not accurately reflect prolonged exposure levels.

TYPICAL MAGNETIC FIELD STRENGTHS

Magnetic fields within homes can vary at different locations and also over time. The actual strength of the field at a given location depends upon the number and kinds of sources and their distance from the location of measurement. Typical values measured in areas away from electrical appliances are of the order of 2 mG.

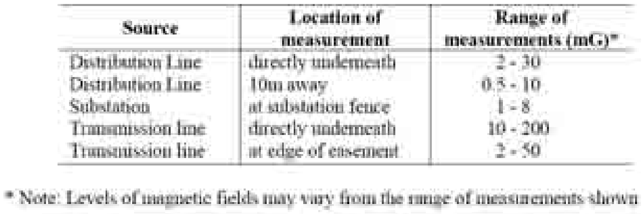
Magnetic fields from individual appliances can vary considerably as well, depending on the way they were designed and manufactured. One brand of hair dryer, for example, may generate a stronger magnetic field than another. In general, appliances, which use a high current (such as those which have an electric motor) will lead to relatively high readings. It should also be noted that different body parts will be exposed to different magnetic field levels from the same appliance, depending on how far that part of the body is from the appliance when in use. Typical values of magnetic fields measured at normal user distance from some common domestic electrical appliances are listed in the following table.



Appliance	Range of measurements (mG)*
Electric stove	2 - 30
Refrigerator	2 - 5
Electric kettle	2 - 10
Toaster	2 - 10
Television	0.2 - 2
Personal computer	2 - 20
Electric blanket	5 - 30
Hair dryer	10 - 70
Pedestal fan	0.2 - 2

HOMES NEAR POWER LINES

The power lines that are present in typical neighbourhoods are called "distribution" lines and they usually carry less voltage than "transmission" lines, which carry very high voltages. As stated earlier, however, it is the current and not the voltage that is associated with the strength of the magnetic field. Therefore, proximity to high-voltage lines will not necessarily give a high reading unless those lines are also carrying a large current. Typical values of magnetic fields measured near power lines and substations are listed in the table below.



Source	Location of measurement	Range of measurements (mG)*
Distribution Line	directly underneath	2 - 30
Distribution Line	10m away	0.5 - 10
Substation	at substation fence	1 - 8
Transmission line	directly underneath	10 - 200
Transmission line	at edge of easement	2 - 50

* Note: Levels of magnetic fields may vary from the range of measurements shown

HOW THE LOADING OF AN AC/DC TRANSFER STANDARD CAN AFFECT YOUR MEASUREMENTS OF AC VOLTAGE AND CURRENT

Neil Faulkner

AC Voltmeters and AC/DC Transfer Standards can cause significant loading errors when measuring many types of sources at the mV level and frequencies above 100 kHz and also below 100 kHz when used with high resistance current shunts. This paper explains the sources of this error, how to measure it and some typical loading errors to be expected with Fluke AC/DC Transfer Standards. This article is a follow up to a preliminary paper on this subject given at NCSL 97 and offers refinements and new information.

INTRODUCTION

In the preliminary paper(1) on this subject it was explained how the input impedance of an AC/DC Transfer Standard or AC Voltmeter can sometimes cause a significant loading of a 50 Ohm source such as the mV ranges of a meter calibrator as shown in Figure 1.

The calibrator uses a resistive divider to get the mV output by dividing down a higher voltage.

The values of the resistors are selected to give a 50 Ohm output impedance. When the AC/DC Transfer Standard is connected to the calibrator output its input impedance loads the 50 Ohms causing the output, voltage to drop. If the input impedance was the same at DC and AC, then this would not cause a problem, assuming the DC also comes from a 50 Ohm divider, but the input impedance drops significantly as the frequency goes up, so this introduces an error in the measurement. The way the AC/DC Transfer Standard is calibrated, this loading is not taken into consideration, so whenever this error is significant, a correction factor for each range and frequency used needs to be applied to the measurement. This is also true for AC Voltmeters.

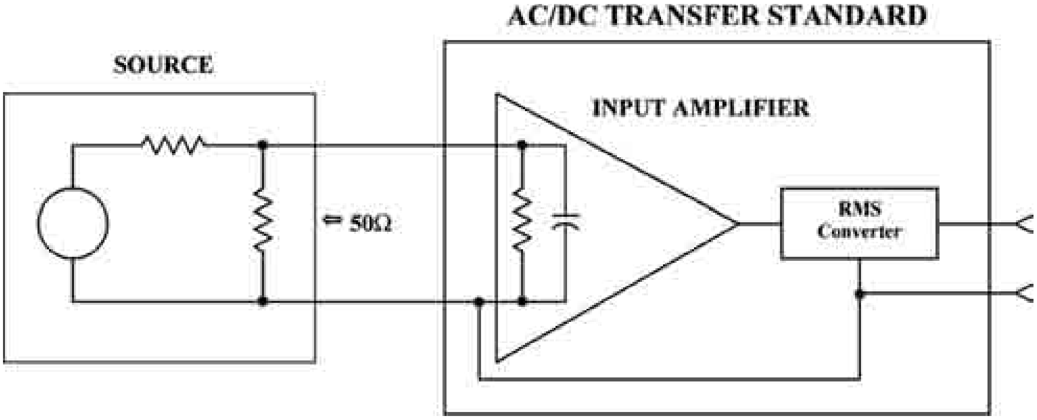


Figure 1. Typical Situation where Loading of a 50 Ohm Source Can Occur

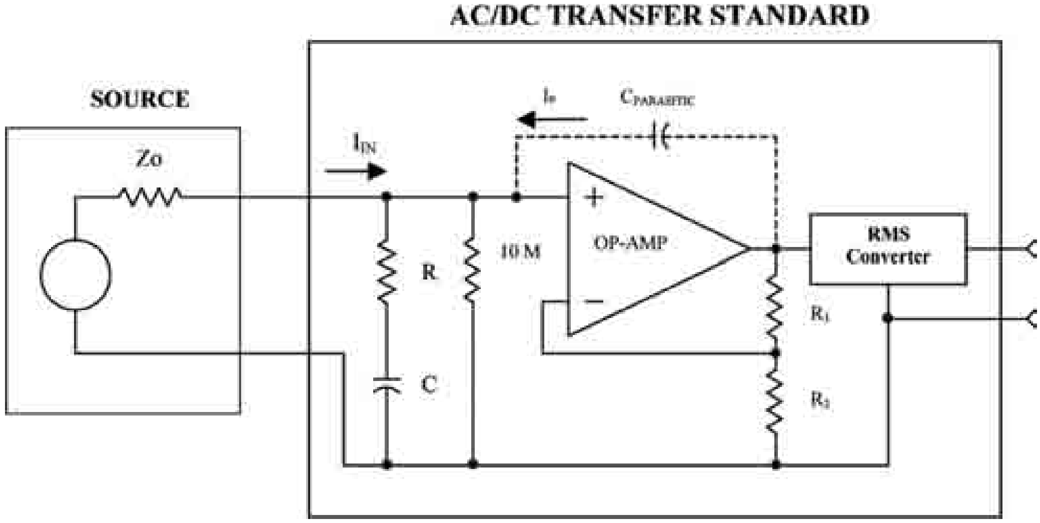


Figure 2. Simplified Diagram of the Input Amplifier of a Fluke 792A

AMPLIFIER CHARACTERISTICS

AC/DC Transfer Standards and AC Voltmeters use an amplifier on the mV ranges to boost the signal to a level the RMS Converter can use. These amplifiers have input resistance and capacitance and there is also some circuit resistance and capacitance as well. The resistance of these amplifiers drops as the frequency goes up, dropping to as low as several hundred kOhms at 1 MHz.

Figure 2 shows a simplified diagram of the amplifier used in the Fluke 792A AC/DC Transfer Standard. The input signal goes to the positive input of the OP-AMP and there is a 10 MOhm resistor across it also. This is a JFET input amplifier, so at DC the total input resistance is 10 MOhm. There is also a very small parasitic capacitance from the output to the input which allows some current to flow back to the input. This is positive feedback, but the negative feedback through R1 and R2 sets the gain and insures good amplifier stability. As the frequency goes up, the amplifier resistance goes down and the current through the parasitic capacitance increases. If a frequency is reached where this current gets as large as the input current, IIN, the input resistance can go to infinity, and above this frequency the current will flow out of the input instead of into it, which looks like a negative resistance. To prevent this, a series RC is placed across the input. As the frequency goes up, this RC draws more current off the source to counteract the current through the parasitic capacitance. This keeps the input resistance positive and consistent from unit to unit. So this RC is a significant part of the input impedance at higher frequencies.

The Fluke 792A has three mV ranges and each has a different input impedance vs frequency and thus different loading. Even though the 220 mV and 22 mV Ranges use the same input amplifier, the loading between the two ranges is different due to changes in the circuit with the change in range.

The 792As produced by Fluke for many years used the same type and vendor of OP-AMP so the loading was very consistent from unit to unit, but then the vendor stopped making the part, so production was switched to a new vendor around October of 1994. This new OP-AMP, though the same type, had more parasitic capacitance so the resistance does go to infinity and then negative at a frequency below 1 MHz on the 700 mV Range and the 22 mV Range. This caused the loading on these ranges to change significantly. The 220 mV range changed only a little.

Figure 3 shows the input resistance of a typical 792A on the 700 mV Range using the original OP-AMP and the one from the new vendor. This shows the input resistance going to infinity at about 340 kHz and negative resistance above that. Figure 4 shows the correction vs. frequency that would be applied. At 1 MHz the correction for the unit with negative input resistance has the opposite sign and nearly the same magnitude as the unit with the original OP-AMP. Figure 5 shows the input resistance vs frequency for the 22 mV Range and Figure 6 the corresponding corrections. Here, the frequency where the resistance goes to infinity is higher and the correction is much smaller and doesn't change sign due to the capacitive loading.

This new OP-AMP shows no signs of instability even though there is enough positive feedback to cause the input resistance to go negative. This is because there is enough negative feedback to insure stability at all frequencies and source impedances. Also the loading can be measured and corrected for just as with the original OP-AMP.

In October of 1998 the new vendor of the OP-AMP discontinued the part and production was switched to still another vendor. The loading with this part is the same as the original vendor on the 220 mV and 22 mV ranges, and on the 700 mV Range it is a little higher. Several units have been evaluated and found to have positive resistance on all ranges and very consistent loading from unit to unit.

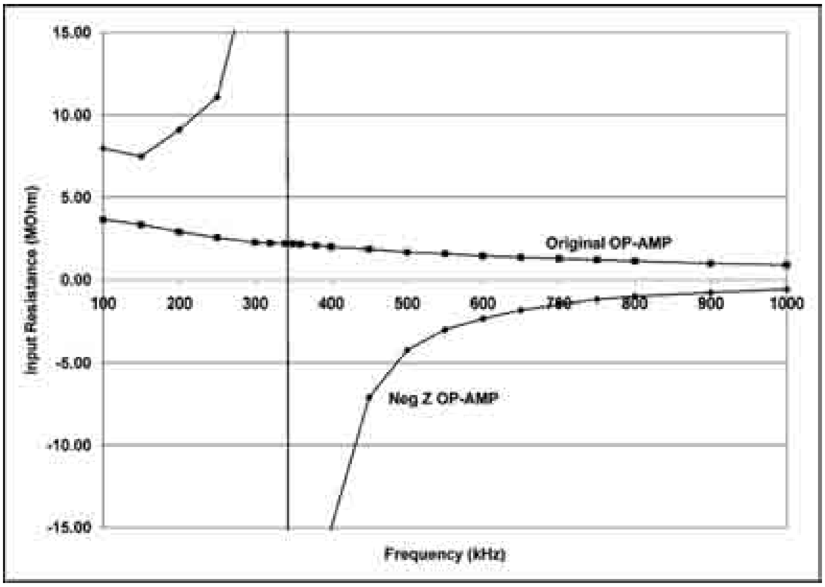


Figure 3. 792A Input Resistance with Different Vendor's OP-AMPs, 600 mV on 700 mV Range

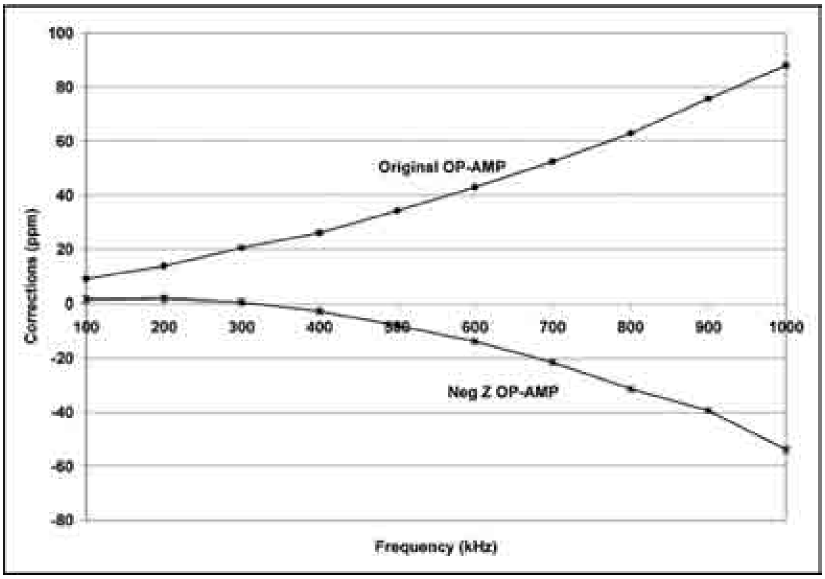


Figure 4. 792A Corrections with Different Vendor's OP-AMPs, 600 mV on 700 mV Range

Figures 7, 8 and 9 show corrections vs frequency plots for each 792A Range for three units with the original OP-AMP, one unit with the negative resistance OP-AMP and two units of the current production. The dashed line in the plots shows the 792A Specification at each frequency. Since only one unit with negative resistance was available for testing, it is not known how the correction varies from unit to unit but for the others these plots give an idea of this variation. All the plots in the previous paper(1) were for units with the original OP-AMP. Also in that paper were plots for the Fluke 5790A AC Voltage Standard. As far as is known, those plots apply for all 5790As produced.

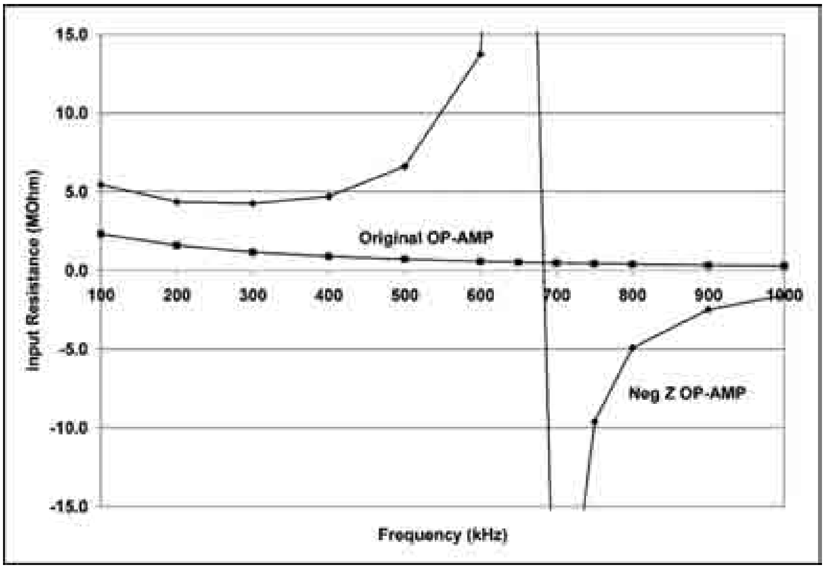


Figure 5. 792A Input Resistance with Different Vendor's OP-AMPs, 20 mV on 22 mV Range

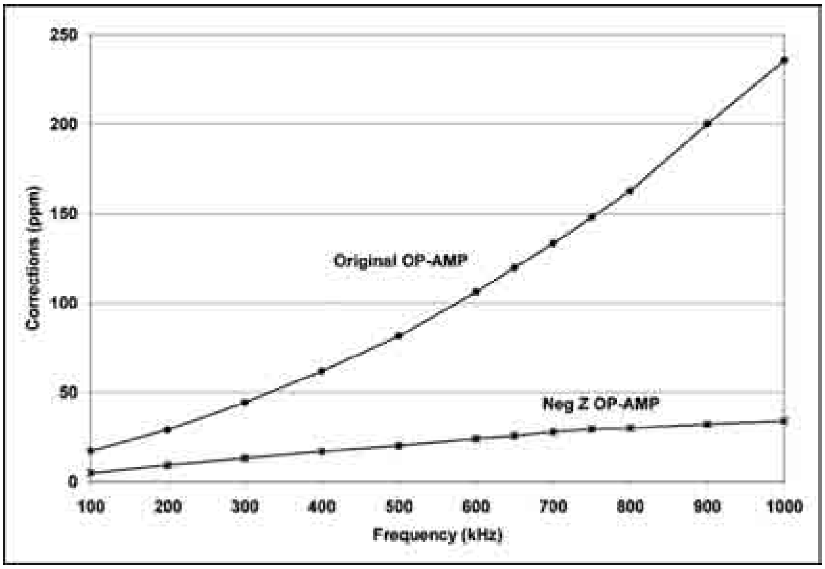


Figure 6. Corrections with Different Vendor's OP-AMPs, 20 mV on 22 mV Range

MEASURING THE LOADING

The loading of a source by a meter can be determined by different methods but one in particular appears to be the most reliable and is simple to implement. The equipment required for this is shown in Figure 10.

A low output impedance source is connected to the input of the 792A or other meter with a 50 Ohm resistor in the HI lead right at the point where the 792A would connect to the source it will be measuring. This insures that the measured loading includes any cable capacitance that would load the source as well as the 792A. A switch right across the resistor allows it to be shorted out during the test. The type of 50 Ohm resistor used is not critical, any low inductance resistor at 1 MHz will give good results like a Carbon Film Resistor. The source needs to be low impedance; a 50 Ohm source will give erroneous results due to the effect of the shunt capacitance. To get a low output resistance at low levels, a resistive divider can be built with metal film or carbon film resistors that has a 1 Ohm output impedance. Only short term stability of the divider is needed.

To make the measurement, set the source to the measurement voltage level and frequency with the 50 Ohm resistor shorted out. Record the meter reading and open the switch and record the reading. The shift in the reading equals the loading and, thus, the correction.

Another method is to measure the input impedance with an RLC Meter. Tests were run with the HP 4284A and, in most cases, it gave acceptable results for all three vendors of OP-AMPs. Best results were obtained with the RLC Meter HI connected to the 792A LO and the Meter LO connected to the 792A HI. The value of resistance in parallel with the capacitance of the 792A on the 700 mV Range is, at 1 MHz, beyond the range of the meter to give accurate measurements of the resistance. Two different meters were tried and one gives a resistance that was twice what it should be and the other was much closer. This resulted in the correction from the first meter to be significantly in error at 1 MHz but the results of the other meter were acceptable. So, a note of caution here, check the accuracy of the meter you are going to use at the resistance and capacitance of the 792A before depending on the results. The lower the resistance, the more accurate the measurement, so the results of both meters were satisfactory on the 220 mV Range and the 22 mV range. Another caution, have the DC output of the 792A floating because if it is grounded, there can be a ground loop through the 792A back to the RLC Meter that will cause a large error at 1 MHz.

A third method for measuring the loading of the 792A, but which will not work in this case above 100 kHz, is to connect an AC Voltmeter to the output of a 50 Ohm source and then note the change in the reading as the 792A is also connected to the source. The reason this doesn't work is that most AC Voltmeters have higher input capacitance than the 792A and it needs to be lower instead for good results. For example, using two 792As, one to read the output of the source and the other as the Unit Under Test, gives unusable results on the 700 mV and 22 mV Ranges and a correction on the 220 mV Range that is about one third too high.

LOADING OF CURRENT SHUNTS

The 792A input resistance can significantly load current shunts when the frequency is as low as a few kHz for shunts of 100 Ohms or more. Figures 11 and 12 show the input resistance vs. frequency for a typical unit of all three vendors of OP-AMPs

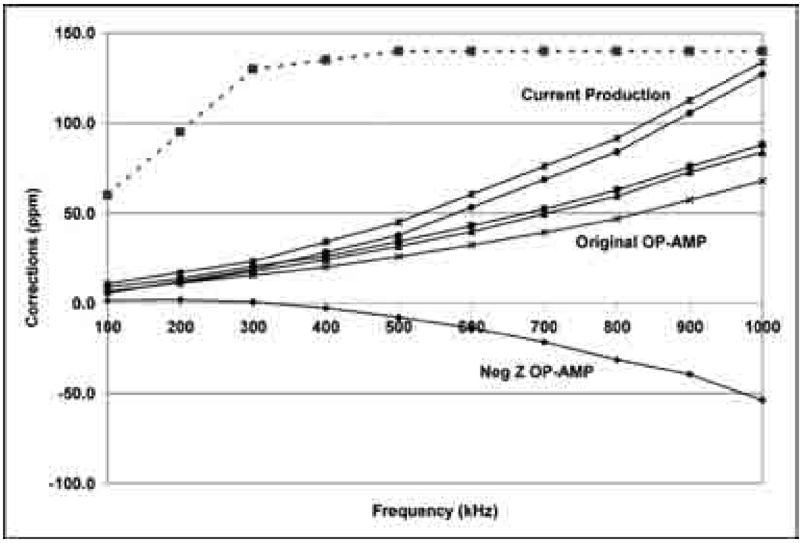


Figure 7. 792A Corrections for a Sample of Units, 600 mV on 700 mV Range

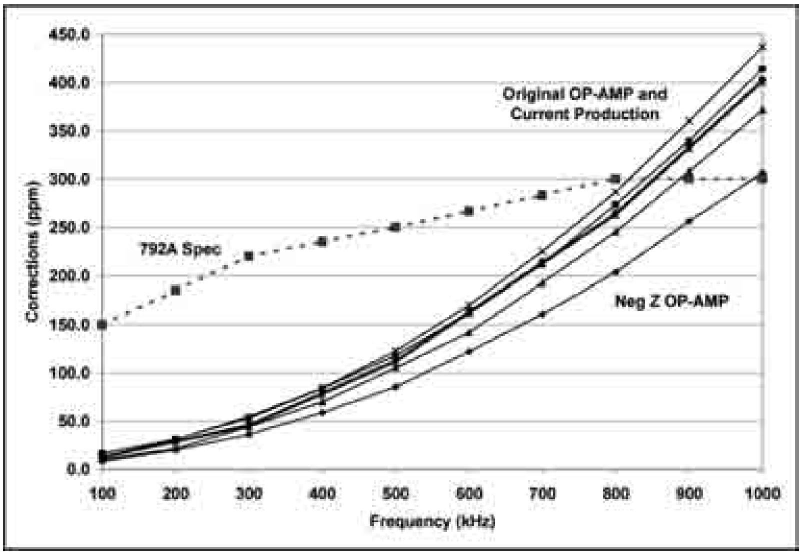


Figure 8. 792A Corrections for a Sample of Units, 200 mV on 220 mV Range

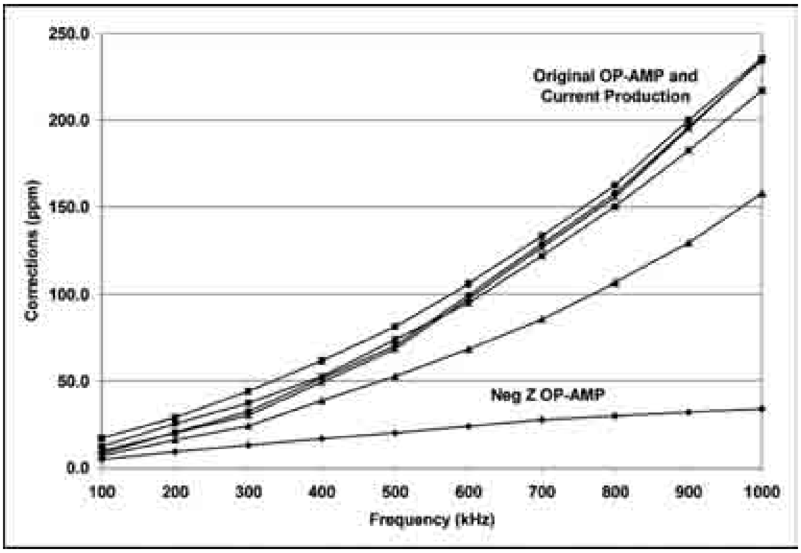


Figure 9. 792A Corrections for a Sample of Units, 20 mV on 22 mV Range

for the 700 mV and 220 mV Ranges respectively. As can be seen, the input resistance is one half of its DC value at 5 kHz and about one forth at 100 kHz. Figure 13 shows the correction that would be required for different values of shunts at 200 mV using the 792A with the original OP-AMP.

The loading and corrections can be measured using the method shown in Figure 10 and described above. Instead of the 50 Ohms, use a resistor of the same value as that of the shunt.

These results show that a higher resistance shunt that is going to be used with a 792A to frequencies above 1 kHz should be calibrated with the 792A that it is going to be used with. If that is not possible, then the loading effect of the 792A that it is calibrated with needs to be subtracted out of the results of the calibration and the loading of the 792A it is going to be used with added in. Another approach would be to increase the uncertainty of the calibration to account for the variation in the loading for 792As.

SUMMARY

The input impedance of AC/DC Transfer Standards and AC Voltmeters can, in some cases, significantly load a 50 Ohm source above 100 kHz and higher resistance shunts below 100 kHz so that corrections for this loading are necessary. As shown for the Fluke 792A, this loading can vary greatly from unit to unit so the loading must be measured for each unit unless it is known that a particular model has consistent loading over all of the production of that model. A reliable method for measuring the loading was given from which the corrections can be determined.

REFERENCES

1. Faulkner, N. and Stott, B., “Loading Effects of AC/DC Transfer Standards”, Paper presented at NCSL 1997, Copy available through Fluke Corporation, Everett, WA.

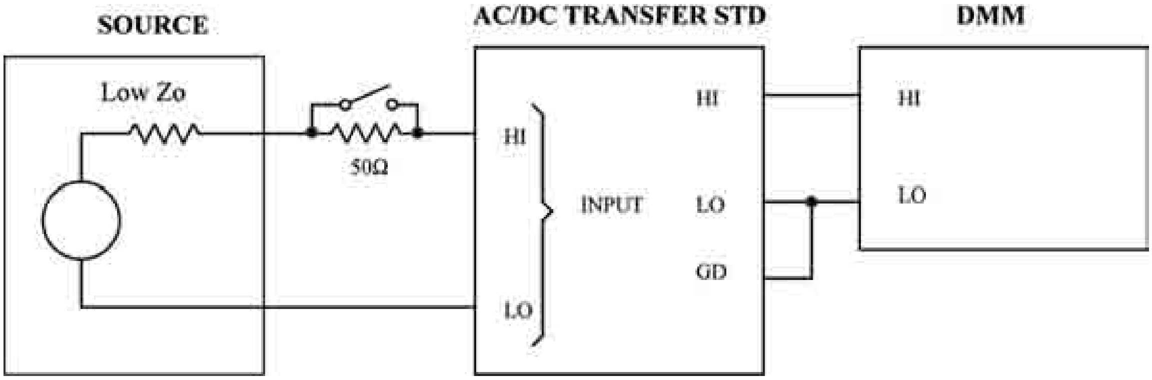


Figure 10. Method for Measuring Loading

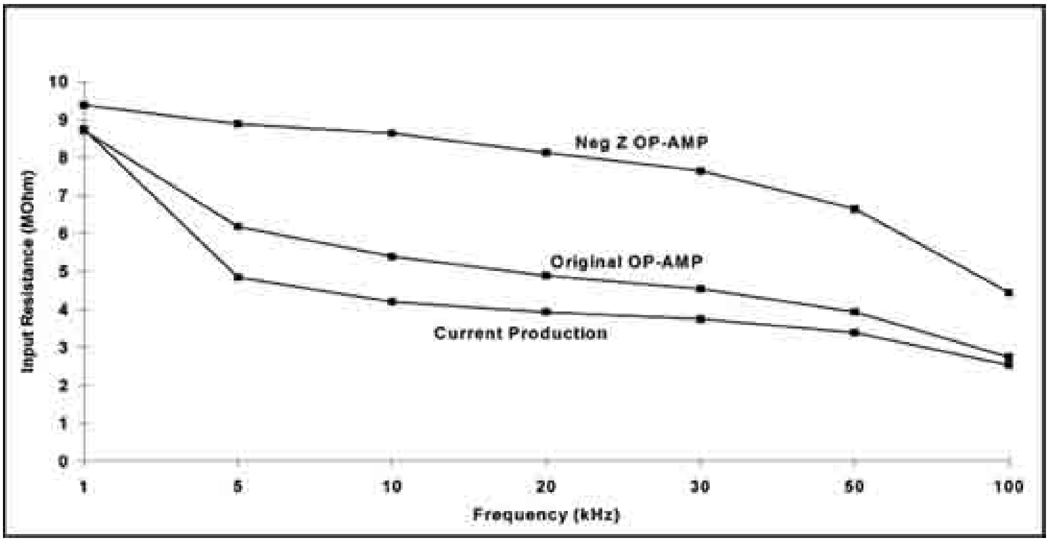


Figure 11. 792A Input Resistance, 1 kHz to 100 kHz, 600 mV on 700 mV Range

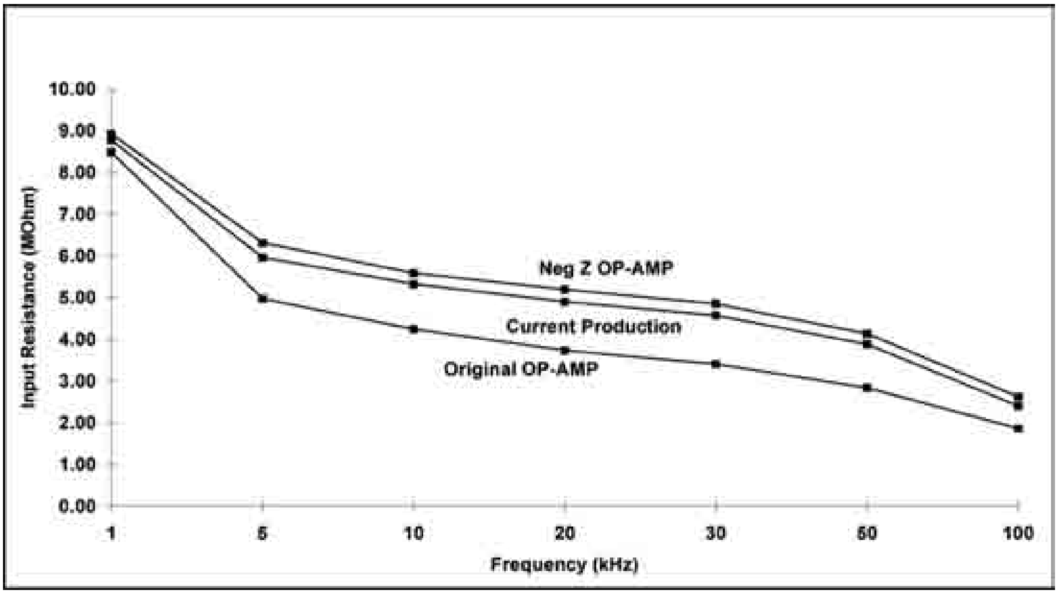


Figure 12. 792A Input Resistance, 1 kHz to 100 kHz, 200 mV on 220 mV Range

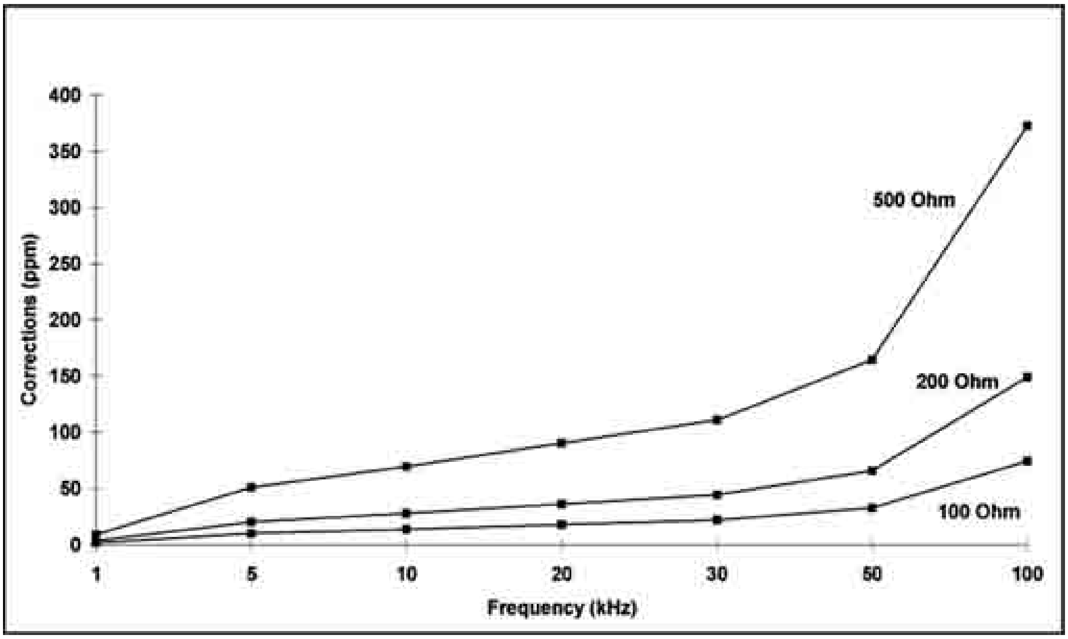


Figure 13. 792A Corrections for Loading of Current Shunts, 200 mV on 220 mV Range

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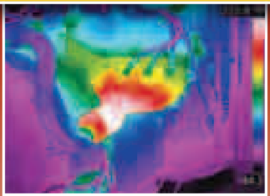

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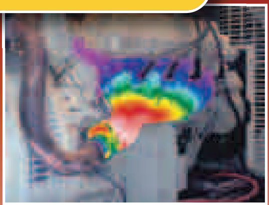

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> — *Jim Phillips*, P.E. T2G Technical Training Group

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